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Magnetoresistive and Magnetocapacitive Effects in Tunnel Magnetic Junctions. Problems and Prospects of Practical Application

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Abstract
This article describes the mechanism of changes in capacitance and resistance in magnetic tunnel junctions upon magnetization reversal of one of the electrodes and presents the results of measurements of the tunnel magnetic resistance and tunnel magnetic capacitance in magnetic tunnel junctions $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ with perpendicular anisotropy electrodes and in magnetic tunnel junctions $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$, where the magnetic electrodes have uniaxial anisotropy in the plane. It shows that when the magnetic electrodes in magnetic tunnel are magnetized, a strong magnetic field gradient appears in the barrier nonmagnetic layer, which causes a spatial redistribution of the concentration of spin-polarized electrons in the magnetic metal/insulator interface region and leads to the appearance of an uneven distribution of electric charge. Such a magnetically induced charge affects the dielectric characteristics of the barrier nanolayer and leads to a change in the resistance and capacitance of magnetic tunnel junctions. Moreover, this effect is most pronounced in tunnel magnetic contacts with magnetic electrodes that have perpendicular anisotropy. The change in resistance during magnetization reversal of magnetic tunnel junctions $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ reached 120% and in magnetic tunnel junctions $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$ it did not exceed 40%. The change in capacitance during magnetization reversal of $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ magnetic tunnel junctions reached values of 110%, and the change in capacitance of $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$ magnetic tunnel junctions it reached values of 45%. In work the scheme of construction of a data carrier on the basis of magnetic tunnel junctions also is given and the principle of record and reading of the information from such carrier is described.

Keywords: Tunnel Magnetic Junctions, Resistance, Capacitance, Perpendicular Anisotropy, Uniaxial Anisotropy in The Plane, Recording Information.

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Introduction

The task of developing and creating small-sized storage media that have a large information capacity, high temperature and radiation resistance and time stability, and are also well protected from unauthorized erasure of recorded information, is relevant and important. Such storage media are most needed today for data management and processing in special small-sized mobile systems where artificial intelligence is used.

In our opinion, the most promising type of storage media for these tasks is magnetic storage media. Magnetic storage media have, in comparison with semiconductor memory, higher temperature, radio-electronic and radiation resistance. In addition, unauthorized erasure of information in magnetic storage media requires a sufficiently powerful magnetic field. Magnetic metal materials are also more durable and significantly cheaper compared to semiconductor materials, which is important for serial production.

The most promising magnetic storage media are media based on tunnel magnetic junctions (MTJs). Although MTJs have been studied for a long time, the prospects of such structures as basic elements of spintronics began to be discussed after they obtained a large change in resistance under the influence of a magnetic field. In recent years, the effect of a change in capacitance during magnetization reversal of one of the magnetic electrodes has also been registered in MTJs. Today, MTJs are considered as one of the basic elements for the development and manufacture of microcircuits in spintronics. The basis for this statement was the results of experimental studies

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in which large values of resistance change (the effect of tunnel magnetoresistance - TMR) and capacitance (the effect of tunnel magnetic capacitance - TMC) were obtained during magnetization reversal of one of the magnetic electrodes in MTJs. The coefficients TMR and TMC are defined as

$$TMR = \frac{R_{max} - R_{min}}{R_{min}}; \quad TMC = \frac{C_{max} - C_{min}}{C_{min}}; \qquad (1)$$

where R_{max}, R_{min} and C_{max}, Cmin are the maximum and minimum values of the MTJ resistance and capacitance during magnetization reversal of one of the electrodes.

Although scientific publications speak about the broad prospect of using MTJ as sensors and components of microcircuits in spintronics, an analysis of their main technical characteristics shows that the scope of their application in practice is limited by a number of factors. The main ones are the high value of the internal resistance of MTJ, and the complexity of reversing the magnetization of one (with a lower coercive force) magnetic electrode. Therefore, the development of microcircuits based on MTJ.

In our opinion, MTJ are also of little promise, as they are not very suitable for creating magnetic field sensors, which is due to their low sensitivity to both the field and the threshold mode of operation. In our opinion, the most promising direction of practical use of MTJ is associated with the development of data recording media on their basis. In essence, MTJ operate in the switch mode, which makes it possible to implement digital data recording with their help, as well as parallel recording and reading mode, which increases the reliability and speed of information processing. MTJs must have a sufficiently high level of temperature, radioelectronic and radiation resistance, and to switch them, it is necessary to apply a sufficiently strong magnetic field, or supply powerful pulses of polarized current to the recording electrodes.

An important factor is that with high protection of the recorded data, the information carrier based on MTJ allows them to be quickly and repeatedly edited and supplemented, which is a great advantage compared to one-time recording media.

It is certainly clear that in modern systems of recording and processing of information it is necessary to provide high speed of recording and high ratio of signal/noise at reading. In addition, the issue of manufacturability and cost of manufacturing of information carriers is important. Cost reduction, automation and reliability of technological processes are also one of the important tasks that arise in the serial production of magnetic information carrier, as well as in the production of any other information carrier. Therefore, the issue of research of characteristics of magnetic tunnel contacts and development of technological principles and schemes of improvement of their technical and operational characteristics is important and urgent.

In this work, we want to consider changes in the microstructure of the interfaces that occur in MTJs during magnetization reversal of magnetic electrodes and the transition from a state with parallel magnetized electrodes to a state with antiparallel magnetized electrodes. We believe that it is the change in the configuration of the structure and direction of the magnetic field in the barrier non-magnetic layer of MTJs that causes a spatial redistribution in the concentration of spin-polarized electrons in the magnetic metal/insulator interface region, a change in the dielectric characteristics of the barrier nanolayer, and is the physical mechanism that leads to TMR and TMC effects in MTJs. Such a mechanism makes it possible to obtain significant values of TMR and TMC effects in MTJ and does not require good matching between the crystal lattices of magnetic electrodes and barrier nanolayer. Moreover, its contribution to the change in the value of TMR and TMC effects is much stronger in MTJ with magnetic electrodes that have perpendicular anisotropy. in MTJ We also want to provide diagrams and describe the principle of recording and reading information from an MTJ-based storage medium.

Magnetic Tunnel Junctions

The results of experimental studies show that the TMR and TMC values depend on the degree of spin polarization of the magnetic electrodes, on the material and structure of the barrier dielectric layer, and on the MTJ manufacturing technology. In the best MTJ samples, the TMC value reaches values greater than 400%, and the TMR value can be greater than 500% [1-4]. Such record-breaking high TMC and TMR values were obtained in Fe/MgO/Fe MTJs using epitaxial manufacturing methods, which ensured high lattice matching of the magnetic electrode and barrier layer.

It is clear that epitaxy technology can be used at the stage of research and experimental development, but it has no prospects for serial production of MTJs due to the complexity and uneconomical nature of production. Moreover, even with the initial ideal matching of the crystal lattices of the magnetic electrode and barrier layer, significant temperature stresses will arise in the MTJ in the region of the magnetic electrode/dielectric barrier layer interface during operation. These stresses arise due to a significant difference in the thermal expansion coefficients of the metal and dielectric lattices, and they should lead to a strong decrease in the TMR and TMC coefficients in MTJs manufactured using the epitaxy technology. In addition, when manufacturing MTJs using the epitaxy technology, high TMR values are obtained in the low-frequency region (less than 1 MHz), and high TMC values are obtained in the low-frequency region (less than 1 kHz) [5].

The very low resonance frequency of the TMC effect is associated, in our opinion, with the ionic component of the dielectric polarization of the MTJ dielectric barrier layer, and it is possible that the structure of the magnetic metal/dielectric barrier layer interfaces of the MTJ largely determines the resonance value of the dielectric polarization. The above expressions for selecting the parameters are in good agreement with the results of experimental studies and allow us to understand the main patterns of the TMC and TMR effects in MTJs in the low-frequency region. However, in experimental studies, and especially in practical developments of MTJs with high rates of TMC and TMR effects, a number of questions arise. The main ones are the following: the influence of the lattice mismatch of the magnetic electrode and the barrier layer, the influence of the structure (poly-, nano- and amorphous) and the tensor of magnetoelectric interaction of the barrier layer material on the magnitude and frequency response of the TMC and TMR effects, the influence of the anisotropy direction (uniaxial anisotropy in the plane and perpendicular anisotropy of the magnetic electrodes), etc. In addition, high values of the TMC and TMR effects were obtained for very low electric field frequencies. And there are practically no data on the magnitude of these effects in the region of megahertz and gigahertz frequencies, although it is the region of such high frequencies that is most important for information processing systems.

In scientific research and experimental development of MTJ, the main direction has been and remains the search for materials and optimization of the design and composition of MTJ in order to obtain maximum values of TMR and TMC, as well as the establishment of patterns and the development of methods for controlling the conductivity of MTJ. There are very few scientific publications that consider the influence of temperature on the technical characteristics of MTJ and the aging process of MTJ, although these issues are very important. It should be noted that the epitaxy technology can be used at the stage of research and experimental development, but it has no prospects for serial production of MTJs due to the false uneconomical nature. Moreover, even with the initial ideal matching of the crystal lattices of the magnetic electrode and the barrier layer, significant temperature stresses will arise in the MTJ in the area of the magnetic electrode/dielectric barrier layer interface during operation. These stresses arise due to a significant difference in the coefficients of thermal expansion of the metal and dielectric lattices. These stresses should lead to a strong decrease in the value of the TMR and TMC coefficients in MTJs in assessing the prospects for practical use of MTJ. Separately, it should be noted that it is necessary to clarify such issues as aging and the effect of temperature on the technical characteristics of MT. Little attention is paid to the study of these characteristics of MTJs in scientific research, but they are very important in assessing the prospects for the practical use of MTJs.

Theoretical calculations show that with ideal lattice matching in Fe/MgO/Fe Fe(001)/MgO(001)/Fe(001) MTJs, major s↑ parallel to the magnetic field) polarized electrons can coherently pass through the barrier layer without attenuation and have a high mean free path, which ensures high conductivity of MTJs with parallel-magnetized electrodes [6-8]. With incoherent tunneling, the probability of passage through the barrier layer does not depend on the spin polarization of the electron in the magnetic electrode, which should be observed when using an amorphous barrier layer [9]. However, in real MTJs, tunneling of major-polarized electrons is not purely coherent, and tunneling through the amorphous barrier layer is not completely incoherent.

The magnitude of the TMR and TMC effects in MTJs depends on the magnetic characteristics of the electrodes and the dielectric constants characteristics of the non-magnetic barrier layer. The electric current through the MTJ is proportional to the probability (T) of the passage of electrons through the tunnel barrier layer [10, 11]. To estimate the magnitude of the current of major polarized electrons s↑ and minor polarized electrons s↓ (antiparallel to the magnetic field), the following expression can be used

$$I_{\sigma;m,m'} = \frac{4e\pi^2}{\hbar} T \int_{-\infty}^{+\infty} g_{1,\sigma}(\varepsilon - eV, \Sigma_1^m) g_{2,\sigma}(\varepsilon, \Sigma_2^{m'}) \times \left[f(\varepsilon - eV) - f(\varepsilon)\right] d\varepsilon, \quad (2)$$

where $g_{i,\sigma}(\varepsilon, \Sigma_i^m)$, $(i = 1,2)$ is the electron density function in the i-th magnetic electrode with magnetization, m=1 is the index for the parallel orientation of the spin and m=2 for the antiparallel orientation, is the energy distribution function for conduction electrons, $f(\varepsilon)$ V is the electric field voltage, e is the electron charge.

At low field voltages V, we obtain an expression for TMR

$$TMR = \frac{G_P - G_{AP}}{G_{AP}} = \frac{2P_1P_2}{1 - P_1P_2}, \quad P_i = \frac{g_{i\uparrow,1} - g_{i\downarrow,1}}{g_{i\uparrow,1}}, \quad (3)$$

The magnetization reversal of the electrode causes a change in the distribution of the density of states of conduction electrons. The magnitude of such a change depends on the magnitude of the exchange interaction of the electron spin with the localized magnetic moment of the magnetic electrode and will differ for parallel and antiparallel magnetization of magnetic electrodes.

When studying the TMC effect in MTJs, the electron drift model (DF model) and the SDD model, which describes the passage of electrons through the barrier, are used. The total capacitance $C_{P(AP)}$ (f, V) of the MTJ at an electric field voltage V is represented as a sequence of capacitance according to the SDD model $C^{SDD}_{P(AP)}(V)$ and capacitance $C^{DF}_{p(AP)}(f, v)$ according to the DF model [8].

$$C_{P(AP)}(f,V) = \left(\frac{1}{C^{DF}_{P(AP)}(f,V)} + \frac{1}{C^{SDD}_{P(AP)}(V)}\right)^{-1}, (4)$$

$$C^{DF}_{P(AP)}(f,V) = \frac{1}{1 - [eV(1-k)(4\Phi_{0,P(AP)})^{-1}]} \times \mathrm{Re}\left[C_{\infty,P(AP)} + \frac{C_{0,P(AP)} - C_{\infty,P(AP)}}{1 + (i2\pi f_{\tau_{P(AP)}})^{\beta_{P(AP)}}}\right], \quad C^{SDD}_{P(AP)}(V) = \frac{eSn_{0,P(AP)}\lambda}{k|V|} \quad (4)$$

The first term in (3) describes the tunneling of electrons through the barrier $\Phi_{0, P(AP)}$, with parallel and antiparallel magnetization of magnetic contacts, S is the area of the electrodes, λ is the characteristic screening length, $n_{0, P(AP)}$ is the density of screening electrons in the interface, and k is the parameter determining the ratio of the dynamic capacitance to the total capacitance. $C_{\infty, P(AP)}$, $C_{0, P(AP)}$, $\beta_{P(AP)}$ – describes the distribution of the relaxation time $\tau_{P(AP)}$ for parallel and antiparallel configurations.

The above expressions for selecting the parameters are in good agreement with the results of experimental studies and allow us to understand the main patterns of the TMC and TMR effects in MTJs in the low-frequency region. However, in experimental studies, and especially in practical developments of MTJs with high rates of TMC and TMR effects, a number of questions arise. The main ones are the following: the influence of the lattice mismatch of the magnetic electrode and the barrier layer, the influence of the structure (poly-, nano- and amorphous) and the tensor of magnetoelectric interaction of the barrier layer material on the magnitude and frequency response of the TMC and TMR effects, the influence of the anisotropy direction (uniaxial anisotropy in the plane and perpendicular anisotropy of the magnetic electrodes), etc. In addition, high values of the TMC and TMR effects were obtained for very low electric field frequencies. And there are practically no data on the magnitude of these effects in the region of megahertz and gigahertz frequencies, although it is the region of such high frequencies that is most important for information processing systems.

Separately, it should be noted that it is necessary to clarify such issues as aging and the effect of temperature on the technical characteristics of MTJs. Little attention is paid to the study of these characteristics of MTJs in scientific research, but they are very important in assessing the prospects for the practical use of MTJs.

Therefore, we believe that a broad study of the patterns of TMC and TMR effects in MTJs is an urgent task and will allow us to clarify known and obtain new scientific results and technical data on MTJs that will be useful in the technology of developing high-frequency MTJs. o, and to develop recommendations and schemes. The task of improving the technical characteristics of MTJs and the development of technological principles and schemes for creating magnetic storage media based on them is both urgent from a scientific point of view and is of high interest for their practical use in the development of magnetic storage media.

Magnetic Field in Magnetic Tunnel Junctions

It is clear that the TMC and TMR effects in MTJs are due to the change in the characteristics of the magnetic field and the magnetic interaction between the magnetic electrodes when the MTJs transition from a state with parallel magnetized electrodes to a state with antiparallel magnetized electrodes. The results of theoretical works [12, 13] and our experimental studies of the interaction of samarium cobalt magnets allow us to present a scheme of the magnetic interaction and magnetic field distribution in MTJs with parallel and antiparallel magnetized magnetic electrodes (Figure 1).

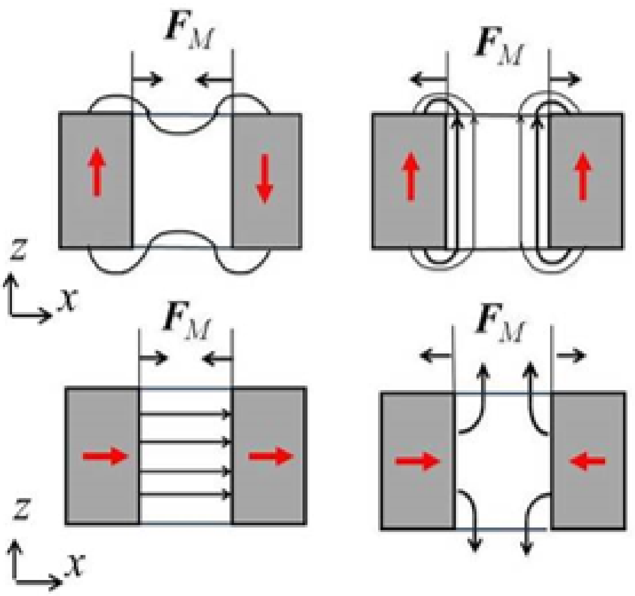

Figure 1: Scheme of magnetic field distribution and magnetic interaction between magnetic electrodes MTJs with different anisotropy of magnetic electrodes: uniaxial anisotropy in the electrode plane and *MTJ*($M_{1\uparrow}M_{2\uparrow}$) and *MTJ*($M_{1\uparrow}M_{2\downarrow}$) - (top); MTJs with perpendicular anisotropy of electrodes: MTJ((M_1M_2) i MTJ((M_1M_2) - (bottom).

It is clear that in MTJs, as in non-magnetic tunnel junctions, in the region of the metal electrode/dielectric barrier layer interface there is a transitional compensatory inverse nanolayer with a thickness of d_i. The thickness of such a compensatory inverse nanolayer depends on the contact potential difference W_C between the material of the magnetic metal electrode and the barrier dielectric layer. The magnitude of the contact potential difference W_C is given by the thermodynamic work function of electrons from the contacting materials. The work function of electrons from a metallic magnetic conductor is in most cases less than the thermodynamic work function of electrons from a barrier dielectric layer (except when a heavily doped semiconductor is used as a barrier layer). Therefore, under the action of such an electric field, conduction electrons move from the metallic magnetic electrode MTJ to the barrier layer and a negatively charged inverse nanolayer with a thickness of. is formed in the magnetic electrode/dielectric barrier layer interface region.

$$d_i \approx A_i\sqrt{(\varepsilon_i\varepsilon_0 W_c)/(\gamma e^2 n_e)}\ , \tag{5}$$

where n_e is the concentration of conduction electrons in the metal electrode, 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 characterizing the transition of conduction electrons to the barrier layer, A_i is the proportionality coefficient.

The thickness of such an inverse nanolayer changes when an electric voltage U_i is applied to the tunnel contact. It increases near one metal electrode, and decreases near the opposite electrode.

$$\begin{aligned} d_{1i} &\approx A_i\sqrt{\varepsilon_i\varepsilon_0(W_c+U_i)/(\gamma e^2 n_e)} \\ d_{2i} &\approx A_i\sqrt{\varepsilon_i\varepsilon_0(W_c-U_i)/(\gamma e^2 n_e)} \end{aligned} \tag{6}$$

In magnetic tunnel junctions, the thickness and dielectric, electro transport and magnetic characteristics of the inverted nanolayer can vary depending on the magnetization state of the magnetic electrodes. In the absence of a magnetic field in the barrier layer in MTJs with demagnetized magnetic electrodes, the characteristics of the transient inverted nanolayer d_i will be determined by the contact potential difference W_C. In MTJs with demagnetized magnetic electrodes, the characteristics of the transient inverted nanolayer will be determined by the contact potential difference W_C. In MTJs with magnetized magnetic electrodes, the dielectric, electro transport and magnetic characteristics of the inverted nanolayers d_i, as well as similar characteristics of the entire barrier layer, with parallel and antiparallel magnetization of the electrodes, can be different. The main reason for the change in the characteristics of the barrier layer of MTJs is the change in the configuration of the magnetic field structure when one of the electrodes in MTJs is magnetized. The change in the dielectric, electrical transport, and magnetic characteristics of inverted nanolayers upon magnetization reversal of one of the magnetic electrodes plays a dominant role in the TMC and TMR effects in MTJs.

As can be seen from Figure. 1, when MTJs transition from a state with parallel magnetization to a state with antiparallel magnetization of the electrodes, the structure of the magnetic field distribution in the barrier non-magnetic layer changes and a strong magnetic field gradient appears near each of the electrodes. In a gradient magnetic field, electrons injected from the magnetic electrode into the inverted nanolayer d_i are subjected to a magnetomotive force $\bar{F}(\vec{s})$, which leads to a spatial separation of major and minor spin-polarized electrons in this nanolayer. The absolute value of the magnetomotive force $\bar{F}(\vec{s})$ is proportional to the magnetic field induction gradient $\nabla\bar{\mathrm{B}}$, and its direction is given by the angle between the electron spin and the magnetic field gradient

$$\bar{F}(\vec{s}) = \nabla(\vec{\mu}_e \cdot \vec{\mathrm{B}}) \tag{7}$$

Analysis of the magnetic field distribution diagram (Figure 1) shows that in MTJs with uniaxial anisotropy in the electrode plane, which coincides with the direction of the z axis, with a parallel orientation of the magnetizations of the electrodes a magnetic repulsive force acts between the electrodes. In the dielectric barrier layer of the MTJ($M_{1\uparrow}M_{2\uparrow}$) near each magnetic electrode, a magnetic field gradient arises, which is directed along the x axis. Along the z axis, the magnetic field strength $H=Hz$ changes much weaker and practically does not change along the y axis: $|dH_z/dx|>>|dH_z/dz|>|dH_z/dy|$. Such a direction of the magnetic field gradient is perpendicular to the polarization direction of both major $n_i(s\uparrow)$ and minor $n_i(s\downarrow)$ polarized electrons and the magnetomotive force acting on electrons in the inverted nanolayer is practically zero. Therefore, with parallel magnetization of electrodes with uniaxial magnetic anisotropy in the plane in the inverted layer $MTJ(M_{1\uparrow}M_{2\uparrow})$ there is practically no separation of major $n_i(s\uparrow)$ and minor $n_i(s\downarrow)$ polarized electrons.

Of course, an inhomogeneous magnetic field will lead to a change in the dielectric constant of the barrier layer material in the interface region due to the magnetoelectric effect and the non-zero value of the magnetoelectric interaction tensor in such a field. Changes in the dielectric constant of the barrier layer material led to a change in capacitance and resistance. Therefore, even with parallel magnetization of electrodes in $MTJ(M_{1\uparrow}M_{2\uparrow})$, their capacitance and resistance may differ from the capacitance of the same MTJs if the magnetic electrodes in them are demagnetized.

With antiparallel magnetization of the electrodes in the MTJ ($M_{1\uparrow}M_{2\downarrow}$) with uniaxial anisotropy in the plane, a magnetic field gradient along the z axis appears in the barrier layer, which can be equal to or even exceed the magnetic field gradient along the x axis. The absolute value of such a gradient can be estimated in a first approximation as

$$\left|\nabla\mathrm{H}_{\|}\right| \approx (H_1 + H_2) / l_0 \tag{8}$$

where H_1 and H_2 are the coercive forces of the first and second magnetic electrodes, and l_0 is the size of the magnetic electrode along the z axis. The magnetomotive force $\bar{F}(\vec{s})$ for such a magnetization of the electrodes in the MTJ($M_{1\uparrow}M_{2\downarrow}$) is not zero, but for major $n_i(s\uparrow)$ polarized and minor $n_i(s\downarrow)$ polarized electrons it has the opposite direction, which leads to the spatial separation of these electrons in the inverted nanolayer d_i. Since the number of major polarized electrons in the inverted nanolayer significantly exceeds the number of minor polarized electrons, a non-uniform distribution of electrons occurs near each of the magnetic electrodes in the inverted nanolayer, i.e. a non-equilibrium electric charge Q_s is formed in it.

Usually in such MTJ($M_{1\uparrow}M_{2\downarrow}$) with antiparallel magnetization of the electrodes, the gradient magnetic field will also cause a change in the dielectric constant of the barrier layer material in the interface region due to the magnetoelectric interaction, and such a change in the dielectric constant with antiparallel magnetization of the electrodes may be greater than for the case of parallel magnetization of electrodes. The capacitance of the MTJ($M_{1\uparrow}M_{2\downarrow}$) with antiparallel magnetized electrodes should be less than the capacitance of the same MTJ($M_{1\uparrow}M_{2\uparrow}$) with parallel magnetized electrodes. The decrease in capacitance in the MTJ($M_{1\uparrow}M_{2\downarrow}$) can be explained by the appearance of additional capacitance in the interface region of the barrier layer due to the inhomogeneous distribution of electrons and the appearance of a non-equilibrium electric charge Q_s The resistance of MTJ($M_{1\uparrow}M_{2\downarrow}$) with antiparallel magnetized electrodes should be greater compared to the resistance of the same MTJ($M_{1\uparrow}M_{2\uparrow}$) with parallel magnetization of the magnetic electrodes, which is due to additional scattering of major $n_i(s\uparrow)$ spin-polarized electrons by inhomogeneity of the electric and magnetic fields.

In $MTJ(\vec{M_1}\vec{M_2})$ with perpendicular anisotropy of magnetic electrodes, with parallel magnetization of electrodes, an attractive force acts between the electrodes. In the dielectric barrier layer, with such an orientation of magnetizations, a practically uniform magnetic field $H=H_x$ arises along the x axis, as well as along the y and z axes, which allows us to write: $dH_x/dx|\approx|dH_x/dz|\approx|dH_x/dy|\sim 0$. The magnetic field strength in the barrier layer is close in magnitude to the magnetic field of perpendicular anisotropy of magnetic electrodes $H_x \approx H_a$.

With perpendicular anisotropy of magnetic electrodes, magnetization reversal leads to even stronger changes in the distribution of the magnetic field in the barrier layer of magnetic tunnel contacts. In the barrier layer, with parallel orientation of the magnetizations of the MTJ($MTJ(\vec{M_1}\vec{M_2})$) between the magnetic electrodes, an almost uniform magnetic field acts, which is directed along the x axis. Magnetization reversal of magnetic electrodes in $MTJ(\vec{M_1}\overleftarrow{M_2})$ with perpendicular anisotropy of electrodes leads to the appearance of a very strong magnetic field gradient $\nabla H_\perp$ near each magnetic electrode, the absolute value of which is much larger compared to the magnetic field gradient for the case of antiparallel magnetization of electrodes in MTJ($M_{1\uparrow}M_{2\downarrow}$) with uniaxial magnetic anisotropy of electrodes in the plane.

$$\left|\nabla\mathrm{H}_{\perp}\right| \approx (H_1 + H_2) / d_0 \, , \tag{9}$$

where H_1 and H_2 are the coercive force of the first and second magnetic electrodes, $d0<<l_0$, d_0 is the thickness of the barrier layer, l_0 is the size of the magnetic electrode along the z axis.

The magnetomotive force $\bar{F}(\vec{s})$ in such $MTJ(\vec{M_1}\overleftarrow{M_2})$ will lead to the spatial separation of major $n_i(s\uparrow)$ and minor $n_i(s\downarrow)$ polarized electrons in the inverted nanolayer d_i. Major polarized electrons are concentrated in the yz–plane at the boundary of the inverted nanolayer with the magnetic electrode, and minor polarized electrons are concentrated in the parallel yz–plane at the opposite boundary of the inverted nanolayer. As a result, a potential difference arises between the boundaries of the inverted nanolayer, which allows us to consider this inverted nanolayer as an additional spin-dependent capacitance. Because of a difference in concentration of major $n_i(s\uparrow)$ and minor $n_i(s\downarrow)$ polarized electrons in the inverted nanolayer arises also the nonequilibrium electric charge charge Q_s.

The electric field of the non-equilibrium spin charge Q_s counteracts the magnetomotive force, which limits the maximum value of the charge Q_0. The estimate of the maximum value of the non-equilibrium charge in the inverted nanolayer d_i can be obtained from the condition of equality of the energy of the electrostatic interaction W_e of the electron charge with the electric field of this charge Q_0 and the energy of the magnetic interaction W_μ of the electron spin μ_e with the magnetic field gradient $\mu_e = W_e$

$$\begin{aligned} W_e &= eQ_0 C_s^{-1} = eU_i \\ W_\mu &= \mu_e \nabla B d_i \end{aligned}, \tag{10}$$

where $C_s = Q_0 U_i^{-1} = A_i \varepsilon_i S/d_i$ - additional spin capacitance that arises in the inverted nanolayer d_i ε_i, is the dielectric constant of the barrier layer material, S - the area of the magnetic electrodes, A_i is the proportionality coefficient.

If, based on equations (8), (9) and (10), we compare the value of the non-equilibrium spin charge Q_0 for magnetic tunnel junctions with perpendicular anisotropy of electrodes and magnetic tunnel junctions with uniaxial magnetic anisotropy of electrodes $MTJ(M_{1\uparrow}M_{2\downarrow})$, then it is clear that the value $Q_0(\overrightarrow{M_1}\overleftarrow{M_2})$ will be significantly larger compared to the value $Q_0(M_{1\uparrow}M_{2\downarrow})$, because the magnetic field gradient in $MTJ(\overrightarrow{M_1}\overleftarrow{M_2})$ is much larger than the magnetic field gradient in $MTJ(M_{1\uparrow}M_{2\downarrow})$.

To determine the resistance of tunnel junctions, the value of the tunnel junctions transparency coefficient D_T is often used, which is inversely proportional to the resistance value $R_T \sim (D_T)^{-1}$ and determines the probability of an electron passing through the tunnel barrier. The value of the tunnel junctions transparency coefficient is determined through the value of the energy height U_T of the tunnel barrier and the thickness of the dielectric barrier layer d_0. At small values of the applied electric voltage V, the value of the tunnel junctions transparency coefficient is defined as

$$D_T = D_0 \exp[-\frac{2}{h} d_0 \sqrt{2m_e(U_T - E_e)}], \tag{11}$$

where $E_e = eV < U_0$, D_0 is a coefficient that depends on the electrical characteristics of the electrode material and the barrier layer, h is Planck's constant, e and m_e are the charge and mass of the electron.

The tunnel barrier height $U_{\uparrow\uparrow}$ and the tunnel resistance of magnetic tunnel junctions with uniaxial magnetic anisotropy of electrodes in the plane with parallel magnetization of contacts will not be equal to the energy height of the tunnel barrier U_0 and the resistance for the same magnetic tunnel junctions with demagnetized electrodes. This difference arises due to the change in the dielectric characteristics of the barrier layer near each of the magnetized electrodes due to the non-zero value of the magnetoelectric interaction thesor of the barrier layer in an inhomogeneous magnetic. In magnetic tunnel junctions with perpendicular anisotropy of magnetic electrodes, the energy height $U_{\uparrow\uparrow}$ of the tunnel barrier and the resistance with parallel magnetization of the electrodes will be practically equal to the energy height of the tunnel barrier U_0 and the resistance of the same magnetic tunnel junctions with demagnetized electrodes. This difference between magnetic tunnel junctions with uniaxial magnetic anisotropy of the electrodes in the plane and magnetic tunnel junctions with perpendicular anisotropy of the magnetic electrodes is due to the fact that with parallel magnetization of the electrodes, a strong magnetic field gradient arises, and with parallel magnetization of the electrodes, the magnetic field in the barrier layer is practically uniform.

With antiparallel magnetization of the electrodes, the transparency coefficient will be smaller in magnitude for both magnetic tunnel junctions with uniaxial magnetic anisotropy and for magnetic tunnel junctions with perpendicular magnetic anisotropy of the electrodes. Such a decrease in the transparency coefficient is associated with the appearance of additional energy barriers that arise near each magnetic electrode. Usually, with antiparallel magnetization of the electrodes, the dielectric characteristics of the barrier layer also change due to the magnetoelectric interaction and the non-zero value of the magnetoelectric interaction tensor in the region of action of a strong gradient magnetic field.

To determine the resistance of magnetic tunnel junctions, you can use formula (11), in which you enter the average value of the thickness $<d_0>$ of the barrier layer and the magnitude of the energy height of the tunnel magnetic barrier $<U_{TMJ}>$, which depends on the orientation of the magnetizations of the magnetic electrodes (2) and (3). But to describe the effect of changing the capacitance of magnetic tunnel junctions, it is better to use the model of three consecutive energy barriers in MTJs that arise in MTJs due to the heterogeneity of the dielectric characteristics of the barrier layer. Such barriers arise near each magnetic electrode due to the non-zero value of the magnetoelectric interaction of the barrier layer material in an inhomogeneous magnetic field transparency coefficient of MTJs $D_{TM(P,AP)}$ in this approach can be represented as the product of the transparency coefficients of all barriers, and the resistance of MTJs as the sum of the successive tunneling resistances for each barrier

$$\begin{aligned} D_{TM(P,AP)} = D_{0(P,AP)} \{ & e^{-\frac{2}{h}[d_{1(P,AP)}\sqrt{2m(U_{1(P,AP)}-E_e)}]} \times \\ & e^{-\frac{2}{h}[d_{2(P,AP)}\sqrt{2m(U_{2(P,AP)}-E_e)}]} e^{-\frac{2}{h}[d_{3(P,AP)}\sqrt{2m(U_{3(P,AP)}-E_e)}]} \} \end{aligned}, \tag{12}$$

where $D_{0(P,AP)}$ is the coefficient that depends on the electrical characteristics of the electrode material and the barrier layer, as well as on the orientation of the magnetization of the electrodes (*P – paraparallel, AP – antiparallel*), $U_{1(P,AP)}$, $U_{2(P,AP)}$, $U_{3(P,AP)}$, and $d_{1(P,AP)}$, $d_{2(P,AP)}$, $d_{3(P,AP)}$ are the effective values of the energy height and thickness of the tunnel barrier near the output magnetic electrode, the central part of the barrier layer, and near the input magnetic electrode.

The effective value of the energy height and thickness of the tunnel barriers will change when the orientation of the magnetization of the electrodes in MTJs changes $U_{iP} \neq U_{iAP}$ and $d_{iP} \neq d_{iAP}$ due to the change in the configuration of the magnetic field distribution and the magnitude and direction of the magnetic field gradient (Figure 1). Changing the structure of the magnetic field distribution in the barrier layer of MTJs leads to a change in the dielectric characteristics of the barrier layer material due to the magnetoelectric interaction and the non-zero value of the magnetoelectric interaction in an inhomogeneous magnetic field [1x]. With antiparallel magnetization of the electrodes in MTJs, it is possible to formally introduce an additional contribution to the height of these barriers due to the Coulomb barrier U_Q, which is associated with the formation of a non-equilibrium spin charge U_s in a gradient magnetic field (10), as well as the spin-dependent barrier $U_{s\uparrow\downarrow}$, which is essentially a pseudobarrier, and it takes into account the increase in resistance for spin-polarized electrons due to their scattering on the magnetic inhomogeneity in the region of the magnetic electrode/dielectric barrier layer interface.

In magnetic tunnel junctions with uniaxial magnetic anisotropy of the electrodes in the plane, when transitioning from one state to state $MTJ(M_{1\uparrow}M_{2\uparrow})$, the effective value of the output barrier for electrons should increase slightly $U_{1AP} \leq P_{U1P}$ due to the contribution of a weak increase in the dielectric constant of the barrier layer material due to magnetoelectric interaction and the contribution of the Coulomb barrier U_Q. The effective value of the barrier near the second input magnetic electrode must grow much more strongly $U_{3AP} > U_{3P}$ to ensure a significant increase in the tunnel resistance in such $MTJ(M_{1\uparrow}M_{2\downarrow})$ [1x, 11]. The effective value of the central barrier with such an orientation of the electrode magnetizations will almost not change $U_{2AP} \approx\approx U_{2P}$.

A significant increase in the tunnel resistance and an increase in the barrier height U_{3AP} in $MTJ(M_{1\uparrow}M_{2\downarrow})$ are associated with spin-dependent scattering of electrons on magnetic inhomogeneity in the barrier layer/magnetic electrode interface region. A certain small contribution to the growth of the height of this barrier in will also be made by an increase in the dielectric constant of the barrier layer material due to the magnetoelectric interaction in the barrier layer/input magnetic electrode interface region and the appearance of a Coulomb barrier U_Q in this region due to the magnetically induced spatial separation of major $n_i(s_\uparrow)$ and minor $n_i(s_\downarrow)$ polarized electrons. It is obvious that the values of the barriers U_{1AP}, U_{1P}, U_{2AP}, U_{2P}, U_{3AP} and U_{3P} will depend on the magnetic and dielectric characteristics of the barrier layer material and the magnetic electrodes.

In magnetic tunnel junctions with perpendicular anisotropy of magnetic electrodes, the energy height of tunnel barriers for conduction electrons should change significantly more when transitioning from a state with parallel magnetized electrodes $(\overrightarrow{M_1}\overrightarrow{MMTJ_2})$ to a state $MTJ(\overrightarrow{M_1}\overleftarrow{M_2})$ with antiparallel magnetization of electrodes. The effective value of the output barrier near the first magnetic electrode should increase slightly $_{U1AP} > U_{1P}$ due to the magnetoelectric increase in the dielectric constant of the barrier layer material and the contribution of the Coulomb barrier U_Q, which arises during the magnetically induced spatial separation of major and minor polarized electrons in a strongly gradient magnetic field. The effective value of the central barrier U_{2AP} in magnetic tunnel junctions with perpendicular anisotropy of magnetic electrodes will also change (most likely increase) $U_{2AP} \approx U_{2P}$, due to the magnetoelectric interaction-induced increase in the dielectric constant of the barrier layer material.

The model of three consecutive barriers not only well describes the change in resistance in magnetic tunnel junctions when switching from parallel to antiparallel orientation of the magnetizations of magnetic electrodes, but also explains the mechanism of TMR effects in MTJs. Such a model provides a good understanding of the TMR effect due to the increase in the effective height of the barriers, and also shows that the increase in the effective height of the barriers due to the increase in the dielectric constant of the barrier layer material and the contribution of the Coulomb barrier due to the spatial separation of major and minor polarized electrons is greater in magnetic tunnel junctions with perpendicular anisotropy of the magnetic electrodes.

When moving on to the description of the TMC effect in magnetic tunnel junctions, it can also be assumed that the total capacitance of MTJs consists of several series capacitances. The basis for this assumption is our consideration, which shows that the barrier layer in MTJs is inhomogeneous and three different regions can be distinguished in it. These are two interface regions near each of the magnetic electrodes and the central part of the barrier layer. The dielectric constant of the barrier layer of MTJs in these regions will be different. The equivalent complex capacitance of MTJs $C_0{}^* = C' - jC''$ can be represented through the series capacitances of these parts

$$C_0{}^* = \frac{C_1{}^* C_2{}^* C_3{}^*}{C_1{}^* C_2{}^* + C_1{}^* C_3 + C_2{}^* C_3}, \qquad (13)$$

where $C_0{}^*$ is the complex capacitance of MTJs; $C_1{}^*$ and $C_2{}^*$ are the complex capacitances of the part of the barrier layer of MTJs near the first magnetic electrode and near the second magnetic electrode, $C_3{}^*$ is the complex capacitance of the central part of the barrier layer of MTJs,

If we assume that the thermodynamic value of the work function for both magnetic electrodes in MTJs is the same, then in the absence of an applied electric field, the electrode capacitances $C_1{}^*$ and $C_2{}^*$ will be practically the same both with parallel $C_{1P}{}^* \approx C_{2P}{}^*$ and with antiparallel magnetization of the electrodes $C_{1AP}{}^* \approx C_{2AP}{}^*$. Usually, when the orientation of the magnetizations of the electrodes changes, the values of the electrode capacitances in MTJs will change $C_{1P}{}^* \neq C_{1AP}{}^*$ and $C_{2P}{}^* \neq C_{2AP}{}^*$.

The dependence of the MTJs capacitance on frequency and applied voltage can be described using formulas (3), which use a number of parameters determined based on the results of experimental measurements [8]. However, these formulas do not show the reasons for the change in the capacitance of magnetic tunnel junctions when the orientation of the electrode magnetizations changes and do not describe the microscopic mechanism of the TMC effect in MTJs. The mechanism of the change in capacitance can be explained by explaining the reason for the change in the value of each component of the capacitance in magnetic tunnel junctions when the orientation of the electrode magnetizations changes.

In the absence of an electric field, when the parallel orientation of the electrode magnetizations changes to antiparallel, the electrode capacitances $C_1{}^*$ and $C_2{}^*$ in the MTJs junction will decrease. In magnetic tunnel junctions with uniaxial magnetic anisotropy of the electrodes in the plane, the decrease in the near-electrode capacitances $C_1{}^*$ and $C_2{}^*$ will occur both due to a decrease in the dielectric constant of the barrier layer and due to the appearance of an additional spin capacitance in the interface region near each of the magnetic electrodes. The decrease in the dielectric constant of the barrier layer in the near-electrode region in such MTJs should occur because, with parallel orientation, a strong magnetic field gradient arises in the barrier layer in the direction perpendicular to the plane of the magnetic electrodes and to the direction of electron polarization in the magnetic electrodes $dH_z/dx >> dH_z/dx > dH_z/dy$. With antiparallel magnetization of the electrode in these MTJs, the magnitude of the magnetic field gradient in the barrier layer is smaller in absolute value, but in the direction of this gradient a component appears that is parallel to the direction of the magnetization of the electrodes and the polarization of major and minor polarized electrons $dH_z/dz \geq dHz/dx >> dHz/dy$. This leads to the appearance in the near-electrode region of the barrier layer of a small spin capacitance, which arises due to the separation of major and minor polarized electrons in the inhomogeneous gradient magnetic field (10) in the magnetic electrodes, and thereby leads to a decrease in the near-electrode capacitances C_1* and C_2*.

In magnetic tunnel junctions with perpendicular magnetic anisotropy of electrodes, when the magnetizations are oriented parallel to the barrier layer, an almost uniform magnetic field is formed, and when the magnetizations are oriented antiparallel, a strong magnetic field gradient arises. The absolute value of this gradient exceeds the values of the gradients described above $dH_x/dx >> dH_x/dz > dHx/dy$, and its direction is parallel to the direction of magnetization of magnetic electrodes in MTJs and the direction of polarization of both major and minor polarized electrons. Therefore, in MTJs with perpendicular magnetic anisotropy, the effective values of the near-electrode capacitances C_1* and C_2* will decrease when the electrodes are oriented antiparallel, mainly due to the appearance of an additional spin capacitance in the interface region near each of the magnetic electrodes. Based on formula (13), for the value of the near-electrode capacitances, we obtain the relation

$$C_{AP1,2}{}^{*} = A_{1,2}\,\frac{C_{1,2P}{}^{*}C_{1,2s}{}^{*}}{C_{1,2P}{}^{*}+C_{1,2s}{}^{*}}\ , \qquad (14)$$

where $C_{P1,2}$*, $C_{AP1,2}$* and $C_{1,2s}$* are the complex values of the near-electrode capacitances 1 and 2 for parallel P and antiparallel AP orientations of the electrode magnetizations, as well as the spin capacitance values for near-electrode capacitances 1 and 2, $A_{1,2} \leq 1$ is the proportionality coefficient.

Since the spin capacitance $C_{1,2s}$* is much smaller than the capacitance $C_{p1,2}$*, the near-electrode capacitances in MTJs for antiparallel magnetization will be smaller than the same capacitance values for parallel magnetization of the electrodes $C_{p1,2}$* $>> C_{AP1,2}$*. The capacitance of the central part of the barrier layer C_3* will change little when the orientation of the magnetizations in MTJs changes $C_{3P}{}^{*} \approx C_{3AP}{}^{*}$.Therefore, the effective value of the complex capacitance of magnetic tunnel junctions should significantly decrease when MTJs transition from a state with parallel magnetization of magnetic electrodes to a state with their antiparallel magnetization.

Under the action of a weak electric field V, when the electron ener $eV_i < U_i$, the thickness of the inverse nanolayer d_i in MTJs with antiparallel magnetized electrodes will slightly increase near the first negative electrode and decrease near the second positive electrode. The value U_i can be determined from the equation $U_i = Q_{si} C_s^{-1} \approx ASed_i[n_i(s_\uparrow)-n_i(s_\downarrow)]C_s^{-1}$, where U_i is the Coulomb barrier, which arises due to the spatial separation of major and minor polarized electrons and the generation of an inverse spin charge in a gradient magnetic field (8), (9) and (10). The effective thickness of the central capacitance C_3^* of the electrodes will change little under the action of a weak electric field $C_{3AP}{}^{*}(V) \approx C3_{AP}{}^{*}(0)$.

The increase in the value d_i will lead to a decrease in the value of the near-electrode capacitance near the negative electrode compared to the same capacitance without an electric field $C_{1AP}{}^{*}(V)$ $C_{1AP}{}^{*}(0)$, which is due to the decrease in the capacitance of a conventional capacitor with an increase in the separation between the electrodes, as well as a decrease in the spin capacitance $C_s^*(V) \leq C_s^*(0)$. The near-electrode capacitance near the second positive electrode should also decrease compared to the same capacitance without an electric field $C_{2AP}{}^{*}(V) < C_{2AP}{}^{*}(0)$, but the main reason for such a decrease will not be a weak change d_i, but a significant decrease in the value of the spin capacitance C_S^* due to a decrease in the inverse spin charge Q_{s2} in the inverse nanolayer near this electrode. The values Q_{s2} will decrease under the action of the polarized current of major polarized electrons $n_1(s_\uparrow)$ from the first (negative) magnetic electrode due to magnetization reversal and compensation of the concentration of major polarized electrons $n_2(s_\uparrow)$ in the inverse nanolayer near this electrode. The analysis shows that even in a weak electric field, the effective value of the complex capacitance of magnetic tunnel junctions should decrease when MTJs transition from a state with parallel magnetization of magnetic electrodes to a state with their antiparallel magnetization.

The results presented above show that the main reason for the change in the effective value of the capacitance in magnetic tunnel junctions when transitioning from parallel to antiparallel orientation of the magnetizations of the electrodes is the appearance of an additional spin capacitance C_s^* near each of the magnetic electrodes. Such spin capacitance arises in the inverted nanolayer d_i in the MTJs barrier nonmagnetic layer due to the spatial separation of major $n_1(s_\uparrow)$ and minor $n_i(s_\downarrow)$ polarized electrons by a high-gradient magnetic field.

It should be noted that the effect of the spatial separation of major $n_1(s_\uparrow)$ and minor $n_i(s_\downarrow)$ polarized electrons on the magnitude of the TMC effect in magnetic tunnel junctions is much greater in the case when the magnetic electrodes in MTJs have perpendicular magnetic anisotropy.

Tunnel Magnetic Junctions $Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_0$ and $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$

The presented analysis of the influence of the magnetic field distribution on the magnitude of the TMR and TMC effects in tunnel magnetic contacts shows that MTJs with perpendicular anisotropy of magnetic electrodes are the most promising elements for creating spintronics microcircuits. To confirm this thesis, we conducted experimental measurements of the TMR and TMC effects in MTJs $Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_{76}$ and $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$, which are practically identical in design and differ in that the former has perpendicular anisotropy of magnetic electrodes and the latter use magnetic electrodes with uniaxial anisotropy in the plane. Magnetic contacts were fabricated by photolithography on a substrate of fused quartz *S=14x14 mm* in the film structure Au/$Tb_{22}Co_5Fe_{73}$/Pr_6O_{11}/$Tb_{19}Co_5Fe_{76}$/Au and Au/$Co_{80}Fe_{20}$/Pr_6O_{11}/$Co_{30}Fe_{70}$/Au. The films were fabricated by magnetron sputtering of alloyed magnetic targets $Tb_{22}Co_5Fe_{73}$, $Tb_{19}Co_5Fe_{76}$, $Co_{80}Fe_{20}$ and $Co_{30}Fe_{70}$, as well as dielectric targets of praseodymium oxide Pr_6O_{11}. First, an Au film with a thickness of *d≈100* nm was deposited on the substrate, and then a magnetic film, a Pr_6O_{11} nanolayer, a magnetic film and an Au film with a thickness of *d≈10* nm were sequentially deposited on it, which was used as a protective coating and as a measuring contact in our MTJs. The thickness of magnetic films was *dm≈ 40* nm. The area of each magnetic electrode was approximately equal to $S \approx 10x5\ \mu^2$. We investigated tunnel contacts with two different thicknesses of Pr_6O_{11} (*d1=1-1.2 nm or d2=1.5-1.8 nm*). The distance between individual tunnel contacts was at least 5 mm.

Amorphous ferrimagnetic films of TbCoFe have a large energy of perpendicular magnetic anisotropy and the value of their coercive force depends on the concentration of components in the film [14]. At *T=300 K* the coercive force of the $Tb_{22}Co_5Fe_{73}$ film is $H1 \approx 3x10^5$ *A/m* and that of the $Tb_{19}Co_5Fe_{76}$ film is $H_2 \approx 1,2x10^5$ *A/m*. When sputtering magnetic polycrystalline CoFe films, a constant field parallel to the substrate plane was applied, which allowed obtaining a high degree of uniaxial anisotropy in the films. At *T=300 K* the coercive force of the $Co_{30}Fe_{70}$ film was equal to $H1 \approx 2,5x10^3$ *A/m* and the $Co_{80}Fe._{20}$ film $H_2 \approx 6x10^3$ *A/m*. Praseodymium oxide Pr_6O_{11} is a wide-gap semiconductor and paramagnet with a large effective magnetic moment but a low Curie temperature $T_K \approx 85$ *K*.

The magnitude of the TMR and TMC effects was measured by the four-probe method and using an bridge in the frequency ranges 0-300 Hz. The measurement signals were recorded and processed by a personal computer. The constant magnetic field was created by an electromagnet. The value of TMR is defined as TMR=(R_{max} – R_{min})/R_{min}, where R_{max} and R_{min} are the maximum and minimum resistances of the structure under investigation. The value of tunnel magnetocapacitance was determined as TMC=(C_P − C_{AP})/C_{AP}, where C_P and C_{AP} is the capacitance at parallel and anti-parallel magnetization of the magnetic electrodes. The measurement results showed that the resistance of MTJs with a smaller thickness of the Pr_6O_{11} barrier nanolayer d_1*=1-1.2 nm* changes more strongly upon magnetization reversal of the magnetic electrodes than in MTJs with a barrier nanolayer thickness d_2*=1.5-1.8 nm*. The capacitance of MTJs with a larger thickness of the Pr6O11 barrier nanolayer d_2*=1.5-1.8 nm* changes more strongly upon magnetization reversal than in tunnel contacts with a smaller thickness of the barrier nanolayer d_1*=1-1.2 nm*. The value of TMR in MTJs $Tb_{22-\delta}Co_5Fe_{73}$/$Pr_6O_{11}$/$Tb_{22-\delta}Co_5Fe_{76}$ with perpendicular anisotropy of magnetic electrodes reached the value of TMR=120% at the thickness of the Pr_6O_{11} nanolayer d_1*=1-1.2* nm and TMR=75% at the thickness of the Pr_6O_{11} nanolayer d_1*=1.5-1.8 nm*. The value of TMC in such MTJs reached the value of TMC=80% at the thickness of the Pr_6O_{11} nanolayer d_1*=1-1.2 nm* and TMC=110% at the thickness of the Pr_6O_{11} nanolayer d_2*=1.5-1.8 nm* (Figure 2).

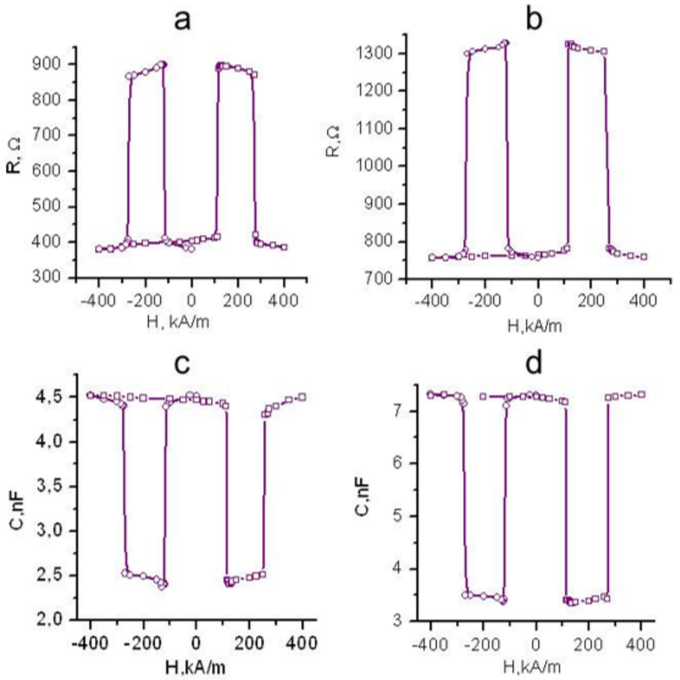

Figure 2: Change in the capacitance and resistance of MTJs with perpendicular anisotropy of magnetic electrodes $Tb_{22-\delta}$-Co_5Fe_{73}/Pr_6O_{11}/$Tb_{19-\delta}Co_5Fe_{76}$: **a** and **c** describes the process when the thickness of Pr_6O_{11} nanolayer is d_1*=1-1,2* nm; **b** and **d** describes the process when the thickness of Pr_6O_{11} nanolayer is d_1*=1,5-1,8 nm*.

The values of TMR and TMC in MTJs $Co_{80}Fe_{20}$/Pr_6O_{11}/$Co_{30}Fe_{70}$ were smaller in absolute value. The value of TMR in such MTJs reached the values of TMR=40% at the thickness of the Pr_6O_{11} nanolayer d_1*=1-1,2 nm* and TMR=30% at the thickness of the Pr_6O_{11} nanolayer d_2*=1,5-1,8 nm*. The value of TMC in such MTJs reached the values TMC=25% at the thickness the Pr_6O_{11} nanolayer d_1*=1-1,2 nm* and TMC=45% at the thickness the Pr_6O_{11} monolayer d_2*=1,5-1,8 nm* (Figure 3).

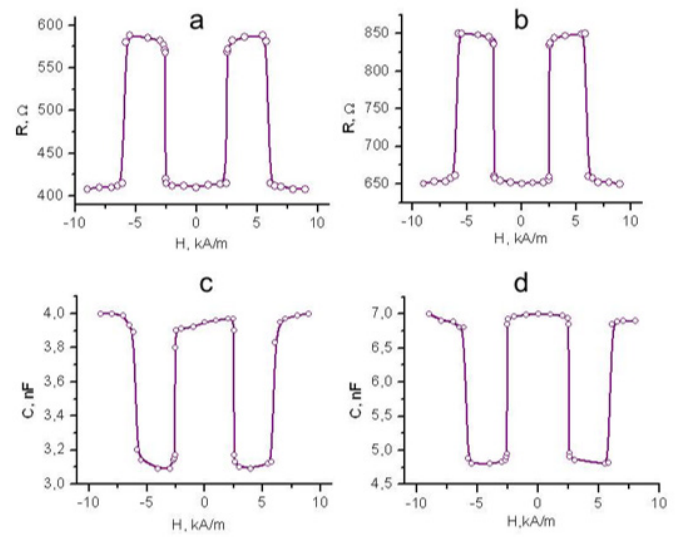

Figure 3: Change in the capacitance and resistance of MTJs $Co_{80}Fe_{20}$/Pr_6O_{11}/$Co_{30}Fe_{70}$, in which the magnetic electrodes have uniaxial anisotropy in the plane: a and c describes the process when the thickness of Pr_6O_{11} nanolayer is d_1*=1-1.2 nm*; b and d describes the process when the thickness of Pr_6O_{11} nanolayer is d_2*=1.5-1.8 nm.*

The results of experimental studies confirm the conclusions of the analysis and show that the influence of the magnetic field gradient on the magnitude of the TMR and TMC effects in MTJs, which leads to the spatial separation of major $n_i(s_\uparrow)$ and minor $n_i(s_\downarrow)$ spin-polarized electrons and the formation of a non-equilibrium charge near each magnetic electrode, is more pronounced in MTJs with perpendicular anisotropy of the magnetic electrodes.

Data Carrier on the Basis of Magnetic Tunnel Junctions

As we noted in the beginning of this article, the most promising direction of practical use of TMR and TMC effects in MTJs is the construction of carriers for recording information based on them. The work also presents a scheme and a method for recording and reading information from a carrier based on MTJs. A feature of such a spin carrier is that it consists of a large number of double MTJs, to which write-read electrodes are connected (Figure. 4). In these MTJs, magnetic electrodes 1, 3 and 4 have different values of coercive force: $H_1 > H_4 >> H_3$, which allows pre-magnetizing magnetic electrodes 1 and 4 in antiparallel directions. The presented scheme for constructing a memory cell based on double MTJs makes it possible to write-rewrite "0" or "1" into a given ml memory cell.

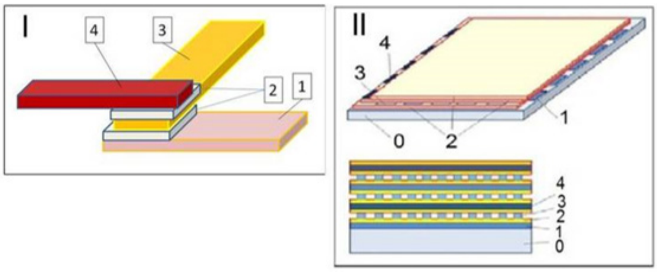

Figure 4: Scheme of the information carrier based on the magnetic tunnel junctions: 0 is the substrate, 1 is magnetic electrodes with a fixed direction of magnetization and coercive force H_1, 2 is the dielectric barrier layer, 3 is magnetic electrode with a small coercive force H_3, 4 is magnetic electrodes with a fixed direction of magnetization and coercive force H_4.

When writing "1" in ml memory cell, a powerful write pulse J_W is applied to 1m and *3l* magnetic electrodes. Moreover, a negative electric field voltage is applied to 1m electrode. When writing "0" in ml memory cell, the same powerful write pulse J_W is applied to 4m magnetic electrode and 3l magnetic electrode. The negative electric field voltage is also applied to *4m* electrode. The amplitude of the write pulse is determined by the magnitude of the current J_W, which must be passed through the tunnel contact to obtain a local magnetization reversal of the magnetic electrode *3l*

$$J_W > \frac{H_a 4\pi\mu_0 S_e he}{\gamma\tau_s\mu_B\mu}, \qquad (15)$$

where S_e and h is area and thickness of the magnetic electrode *3l*, μ and τ_s is magnetic permeability and relaxation time of spin polarization in the material of this electrode, $\gamma<1$ is coefficient characterizing the magnitude of spin polarization in the magnetic materials of the electrodes 1m or 4m, e is electron charge, μ_0 is absolute magnetic permeability.

When reading information from ml memory cell, 2 the same read pulses J_R are applied simultaneously to the *1m* electrode and *3l* electrode, as well as to the *4m* electrode and *3l* electrode. The polarity of the read pulse coincides with the polarity of the write pulse, but its amplitude J_R is much smaller than JR $J_R << 0{,}1J_W$.

The information recorded in the ml memory cell ("0" or "1") can be recorded by measuring the difference in the amplitudes of the read pulses, or by measuring the difference in the phase shift between these pulses. In the first case, the change in the resistance of the double MTJs is used when recording information, that is, the effect of changing the magnetoresistance TMR is used, and in the second case, the effect of changing the magnetocapacitance TMC is used. The method of measuring the phase difference between the signals is more sensitive and accurate, which increases the reliability of the operation of information recording devices based on double MTJs, in which the TMC effect is used. The magnitude of the phase shift between the read pulses will depend on the difference in capacitance between the magnetic contacts *1m-3l* and *4m-3l* $\Delta\Phi = f(C_{13} - C_{43})$. If the ml-th memory cell contains "1", then the capacitance between the contacts *1m-3l* will be greater than the tunnel magnetic capacitance tunnel magnetic capacitance between the contacts *1m-3l* will be less than the capacitance between the contacts *4m-3l*.

Conclusion

In the final part of our work, we would like to note that in order to implement the effects of magnetic tunnel resistance and magnetic tunnel capacitance, a number of important scientific and technological problems must be solved. The most important is the issue of high TMR and TMC coefficients in the high and ultra-high frequency range. Unfortunately, today record high TMR and TMC values in MTJs are obtained not only when using epitaxy technology, which is not very promising for industry, but such high indicators are registered in the low and medium frequency range. It is clear that the maximum values of TMR and TMC in MTJs will be set by the resonant frequencies of the dielectric polarization of the barrier insulating layer material, which depend on the parameters of the electron-ion coupling and the structure of the material. The low-frequency high values of TMR and TMC, which are currently obtained in MTJs, are associated, in our opinion, with the ionic polarization of the dielectric characteristics of the barrier insulating layer material. The most high-frequency component of the dielectric polarization of the material is its electronic component. Therefore, in further scientific research and development of MTJs, it is necessary to focus on materials and structures in which the electronic component of the dielectric polarization of the barrier layer material makes a significant contribution to the value of TMR and TMC.

The results of our research show that tunnel magnetic contacts with magnetic electrodes that have perpendicular anisotropy are not only an interesting object for studying the tunnel magnetic capacitance effect, but they may also have good prospects for practical use in the development of a medium for magnetic information recording.

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