Research Article

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Magnetic Storage Media Based on Tunnel Magnetic Junctions

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Abstract
This paper analyzes the prospects for the use of magnetic information carriers based on magnetic tunnel junctions (MTJs), considers the main mechanisms of the effects of tunnel magnetoresistance (TMR) and tunnel magnetocapacitance (TMC) in MTJs, and presents the results of experimental studies of the influence of temperature and pulsed electric current density through tunnel magnetic contacts on the magnitude of the TMR and TMC coefficients in magnetic tunnel junctions Tb22Co5Fe73/Pr6O11/Tb19Co5Fe76 and Co80Fe20/Pr6O11/Co30Fe70, and also presents a scheme for recording and reading information from a magnetic information carrier based on double MTJs. The paper shows that a magnetic information carrier based on MTJs has good prospects for use in autonomous control systems using artificial intelligence, and also highlights factors that affect the technical characteristics of information carriers of this type.

Keywords: Artificial Intelligence, Information Recording, Tunnel Magnetic Contacts, Magnetoresistance, Magnetocapacity, Thermal Effect, Pulsed Current

Introduction

The development of modern automated control and data processing systems involves the widespread use of artificial intelligence (AI). An important element of such systems are information carriers, in which the algorithm for operating and controlling the main blocks and components of the system, as well as programs for processing the received data, is already recorded. In most cases, semiconductor-based information carriers are already used and will be used in the future in systems with artificial intelligence. However, in some cases, there is a need for small-sized information carriers that have increased thermal, thermoelectric, time and radiation resistance and are well protected from unauthorized erasure of recorded information. Such information carriers are primarily needed in military developments, as well as in automated control systems that operate in difficult technological conditions and elevated temperatures, as well as for use in special autonomous small-sized mobile devices in aviation, sea and land transport. Moreover, the widespread use of artificial intelligence in such processes and objects will lead to an increase in the need for such information carriers.

Magnetic media can also be included in the class of media with enhanced functional and operational technical characteristics. Magnetic media have, compared to semiconductor memory, higher temperature, radio electronic and radiation resistance. In addition, unauthorized erasure of information on magnetic media requires a sufficiently powerful magnetic field. Magnetic metal materials are also more durable and cheaper compared to semiconductor materials, which is also important for mass production Analysis of the main technical characteristics of magnetic tunnel junctions (MTJs) shows that the scope of their practical application is limited by a number of factors. The main ones are the high value of internal resistance and the complexity of controlling the conductivity of MTJs, which is implemented through the magnetization reversal of a magnetic electrode with a low coercive force. Magnetic tunnel contacts cannot be used to create magnetic field sensors, which is due to the low sensitivity to the field and the threshold mode of their operation. In fact, MTJs operate in the switch mode, which allows implementing the parallel recording-reading mode of information and a magnetic information carrier based on MTJs will be able to provide high reliability and speed of information processing. Such an information carrier will have a sufficiently high level of temperature, radio electronic and radiation resistance, as well as a high level of protection against unauthorized erasure of data, since to erase the recorded information, it is necessary to apply a sufficiently strong magnetic field, or to apply powerful current pulses to special recording electrodes. An important factor is that with high security of recorded data, a magnetic information carrier based on MTJs allows for quick and repeated editing

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and supplementing of recorded information, which is a great advantage compared to disposable recording media. The above facts allow us to conclude that the most promising direction of practical use of MTJs is associated with the development of a media base for recording information on them.

Today, it can be considered that the most promising magnetic information carriers are magnetic media based on MTJs. Although this class of objects has been studied for a long time, the prospects for their practical use began to be discussed after obtaining in them a large change in resistance (tunnel magnetoresistance effect - TMR) and a change in capacitance (tunnel magnetocapacity effect - TMC) during magnetization reversal of one of the electrodes and the transition of MTJs from a state of parallel magnetization to a state with antiparallel magnetization of the magnetic electrodes [1-5].

The issue of high-frequency switching of MTJs and changes in their conductivity and capacitance, which is realized through the magnetization reversal of a magnetic electrode with a low coercive force, is a complex technical problem. The scientific literature considers the possibility of changing the direction of the magnetic moment of the control magnetic electrode of MTJs under the action of a magnetic current through special electrodes or under the action of a magnetic field of an injected spin-polarized current, magnetization reversal of one of the electrodes due to a change in the exchange interaction between the magnetic electrodes, as well as due to electrically controlled magnetic anisotropy, which is considered the most promising method of reducing the magnetic reversal energy of magnetic nanolayers [6-9]. However, when the magnetic electrode is remagnetized by electric field pulses of injected spin-polarized current or electrically controlled magnetic anisotropy, current pulses with very high current density pass through the MTJs. Such current pulses can lead to changes in the TMR and TMC values in the MTJs.

The main efforts of scientific research on magnetic tunnel junctions are aimed at establishing the mechanisms of TMR and TMC, developing methods for controlling the conductivity of MTJs, and optimizing their design and composition in order to obtain maximum values of TMR and TMC. Most scientific studies consider methods for controlling the conductivity of MTJs, but there is almost no data on how the magnitude of the tunnel magnetoresistance and tunnel magnetic capacitance changes when switching the conductivity of MTJs not by a magnetic field, but by an electric current, and there are absolutely no results on how long cycles of multiple magnetization reversal of MTJs by a non-magnetic field affect changes in TMR and TMC. Such data are necessary for their practical use. Very few works have been devoted to studying the influence of temperature and aging processes on the technical characteristics of tunnel magnetic junctions, although these issues also largely determine the possibility of using MTJs in memory elements and other spintronic devices.

This paper presents the results of our studies of the influence of temperature and pulsed electric current density through tunnel magnetic contacts on the value of TMR and TMC in MTJs $Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_{76}$ with perpendicular anisotropy of electrodes and in MTJs $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$, where the magnetic electrodes have uniaxial anisotropy in the plane.

Experimental Methodology and the Value of the TMR and TMC Coefficients

The studies used practically identical MTJs in design, which differ only in that the MTJs Tb22Co5Fe73/Pr6O11/Tb19Co5Fe76 electrodes are amorphous films with strong perpendicular anisotropy in structure, and the MTJs Co80Fe20/Pr6O11/Co30Fe70electrodes are polycrystalline films with uniaxial anisotropy in the plane. MTJs were fabricated by photolithography in the film structure Au/Tb22Co5Fe73/Pr6O11/Tb19Co5Fe76/Au and Au/Co80Fe20/Pr6O11/Co30Fe70/Au, which were deposited on a fused quartz substrate by magnetron sputtering of alloy magnetic targets Tb22Co5Fe73, Tb19Co5Fe76, Co80Fe.20 and Co30Fe70, as well as targets of praseodymium oxide and gold. To obtain uniaxial anisotropy of magnetization in the film plane in the CoFe films, a constant magnetic field was applied during their sputtering in the substrate plane.

The thickness of magnetic films was equal to dm≈ 40 nm and the thicknesses of Au gold films were d1≈50 nm and d2≈10 nm. The thickness of the Pr6O11 barrier nanolayer was equal to di≈1,8-2 nm. The area of each magnetic electrode was approximately equal S=50-70 μ2. The distance between individual tunnel contacts was at least 5 mm.

The value of the tunnel magnetoresistance was measured by the four-probe method, and the magnetocapacitance was measured by the measuring ac bridge. The temperature of the MTJs was maintained using a thermal chamber. When studying the influence of the current on the characteristics of the MTJs, a given number of electrical pulses with a duration of τ ≈20 ns were applied to the sample and an electronic system was used to limit and stabilize the amplitude of the current through the MTJs.

Typical dependences of the resistance and capacitance of our MTJs are presented in Fig. 1. The value of magnetic tunnel resistance magnetocapacitance of MTJs was defined as TMR= (Rmax–Rmin)/Rmin, and the value of magnetic tunnel magnetocapacitance was defined as TMC= (CP−CAP)/CAP, where Rmax and Rmin are the maximum and minimum resistances of MTJs, and CP and CAP are the capacitance at parallel and anti-parallel magnetization of magnetic electrodes. The value of TMR in MTJs Tb22Co5Fe73/Pr6O11/Tb19Co5Fe76 was equal to TMR = (63 – 67) % at temperature T=300 K and the value of TMC was equal to TMC= (40 – 45) %. The value of TMR in MTJs Co80Fe20/Pr6O11/Co30Fe70 was equal at temperature T=300 K TMR= (27 – 30)% and the value of TMC was equal to TMC= (27– 30) %.

The rather high values of the coefficients TMR and TMC in our MTJs indicate that the electron tunneling is not completely incoherent, although the amorphous barrier layer Pr6O11 in MTJ Tb22Co5Fe73/Pr6O11/Tb19Co5Fe76 is with a high probability amorphous. The independence of the tunneling probability from the electron spin polarization during incoherent tunneling should give lower values of TMR and TMC in MTJs [1]. This once again shows that in real MTJs the tunneling is not completely incoherent or coherent, which should be observed in structures of the Fe(001)/MgO(001)/Fe(001) type [3-7].

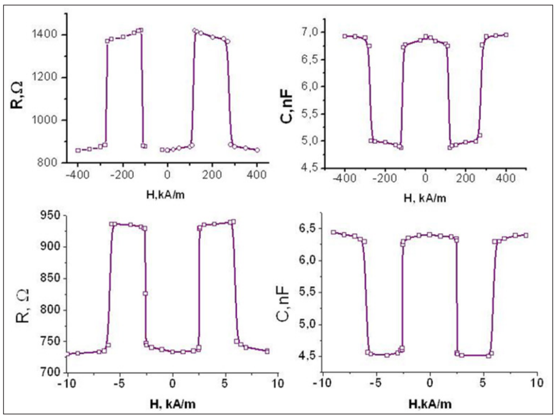

Figure 1: Change In The Resistance And Capacitance Of Mtjs Tb22co5fe73/Pr6o11/Tb19co5fe76 (Top) And Mtjs Co80fe20/Pr6o11/Co30fe70 (Bottom).

Inhomogeneous Magnetic Field and TMR and TMC Effects

We believe that the main reason for the TMR and TMC effects in MTJs is a strong change in the magnitude and direction of the magnetic field gradient in the magnetic metal/insulator interfaces when MTJs transition from a state with parallel magnetized electrodes to a state with antiparallel magnetized electrodes. Based on the results of, the scheme of magnetic interaction and magnetic field distribution in MTJs with parallel and antiparallel magnetized magnetic electrodes can be represented as (Figure. 2) [8-10].

This diagram shows that when one of the electrodes of the MTJs is magnetized, it causes a strong change in the configuration of the magnetic field structure in the barrier layer and changes the nature of the magnetic interaction between the electrodes. Moreover, the structure of the magnetic field in the barrier layer and the nature of the magnetic interaction between the electrodes are different for uniaxial anisotropy of the magnetic electrodes in the $MTJ(M_{1\uparrow}M_{2\uparrow})$ plane and for their perpendicular anisotropy $MTJ(\vec{M}_1\vec{M}_2)$.

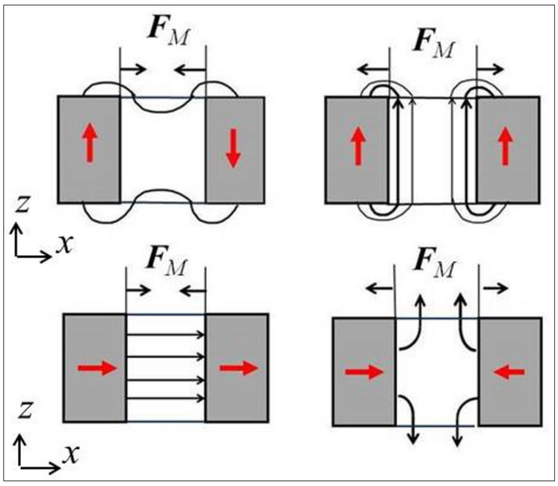

Figure 2: Scheme of the configuration of the magnetic field and magnetic interaction between the magnetic electrodes of MTJs with different anisotropy of the magnetic electrodes: uniaxial anisotropy in the electrode plane $MTJ(M_{1\uparrow}M_{2\downarrow})$ and $MTJ(M_{1\uparrow}M_{2\uparrow})$ - (top); perpendicular anisotropy $MTJ(\vec{M}_1\vec{M}_2)$ and $MTJ(\vec{M}_1\overleftarrow{M}_2)$ - (bottom).

In magnetic electrodes with uniaxial anisotropy in the plane, which coincides with the direction of the z axis, with a parallel orientation of the magnetizations between the electrodes, a magnetic repulsive force acts along the x axis. In the MTJs barrier layer, a magnetic field gradient appears near each magnetic electrode, 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: |dHz/dx|>>|dHz/dz|>|dHz/dy|. With antiparallel magnetization of electrodes with uniaxial anisotropy in $MTJ(M_{1\uparrow}M_{2\downarrow})$, an attractive force acts between them along the x axis. The magnetic field in the barrier layer changes not only along the x axis, but also along the z axis. Along the y axis, the magnetic field strength practically does not change: |dHz/dx|>|dHz/dz|>>|dHz/dy|.

In MTJs with perpendicular anisotropy of electrodes, with parallel magnetization of electrodes $MTJ(\overrightarrow{M_1}\overrightarrow{M_2})$, an attractive force acts between magnetic electrodes, which is directed along the x axis. In the barrier nanolayer of MTJs along the x axis, an almost uniform magnetic field H=Hx is formed, the intensity of which is close to the field of perpendicular anisotropy of magnetic electrodes $H_x \approx H_a$. In this case $dH_x / dx |> |dH_x / dz| \approx |dH_x / dy| \sim 0$ With antiparallel magnetization of the electrodes $MTJ(\overrightarrow{M_1}\overleftarrow{M_2})$ (a repulsive force acts between the magnetic electrodes along the *x* axis) the strong magnetic field gradient appears in the insulating barrier layer along the x direction. The absolute value of the magnetic field strength decreases from the maximum value $H_{xo} \approx H_a$ to zero with increasing distance from the magnetic electrode to the middle of the insulating barrier layer. In the other two directions *y* and *z*, the magnetic field strength practically does not change: $dH_x / dx| >> |dH_x / dz| \approx |dH_x / dy|$.

Such an inhomogeneous magnetic field with a high gradient value in one of the directions will lead to a change in the dielectric constant ε of the barrier nanolayer due to magnetoelectric interactions, which in principle can give a change in the resistance of the MTJs. However, in non-polarized and non-magnetic materials, the magnitude of the change in the dielectric constant ε due to magnetoelectric interactions is small, which does not allow obtaining high values of TMR coefficients in MTJs due to such changes in ε.

In theoretical works, it is believed that the tunneling resistance of MTJs is due to the dependence of the electron density at the Fermi level on their spin polarization, as well as the probability of tunneling through the barrier nanolayer, which is different for different electron states. The effect of spin-dependent tunneling depends on the structural and electronic properties of the tunnel junction as a whole, including the tunnel layer and the interface. Tunneling conductivity depends not only on the electron density at the Fermi level, but also on the probability of tunneling, which is different for different electron states. The dependence of the MTJ resistance on the mutual orientation of the magnetization and the TMR effect can be obtained from the average probability of passage through the barrier nanolayer of the components of the spin-polarized current with major $s\uparrow$ and minor $s\downarrow$ polarization [7]. At a small value of the voltage V applied to the MTJs, the TMR value can be described in terms of the magnetization of the magnetic electrodes

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

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

However, the given formula does not explain the high experimentally obtained values of TMR=400-500%. Therefore, it is believed that such high TMR values are achieved due to scattering in the barrier nanolayer of electrons with major $s\uparrow$ and minor $s\downarrow$ polarization [6]. With absolute consistency of the crystal structure of the magnetic electrodes with the crystal structure of the barrier nanolayer, electrons with major $s\uparrow$ polarization pass through this nanolayer without scattering, and with antiparallel magnetization, they are strongly scattered at the interface of the barrier nanolayer with the input magnetic electrode, which allows obtaining high TMR values in MTJs.

High values of TMC coefficients in MTJs are explained by the fact that, that when the magnetic electrodes are antiparallel magnetized, the spin-polarized current components with major $s\uparrow$ and minor $s\downarrow$ polarizations diffuse from the magnetic electrode into the barrier nanolayer to different depths, which leads to a difference in the distribution of electron density with major $s\uparrow$ and minor $s\downarrow$ polarizations and the formation of electric dipoles [5,11]. Such a charge dipole creates an additional capacitance, which is responsible for the TMC effect in MTJs.

To describe the TMC effect in MTJs, the capacitance value $C_{P(AP)}(f,V)$ is represented as a sequence of two capacitances: $C^{SDD}{}_{P(AP)}(V) = eSn_{0,P(AP)}\lambda(k\,|V\,|)^{-1}$ is the capacitance describing the spin-dependent passage of electrons through the barrier (SDD model) and $C^{DF}{}_{P(AP)}(f,V)$

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

is the capacitance describing the spin-dependent diffusion and drift of electrons (DF model)

$$C_{P(AP)}(f,V) = \left(\frac{1}{C^{DF}{}_{P(AP)}(f,V)} + \frac{1}{C^{SDD}{}_{P(AP)}(V)}\right)^{-1} \quad (2)$$

Here the barrier $\Phi_{0,P(AP)}$ is the barrier for parallel and antiparallel magnetization of the contacts, e is the electron charge, S is a junction area, λ is a characteristic screening length, n0,P(AP) is a screening charge density at the interface and k is the parameter determined by the contributingratio of the dynamic capacitance to the overall capacitance [5]. $C_{\infty,P(AP)}$, $C_{0,P(AP)}$ are the high-frequency and DC capacitances, and $\beta_{P(AP)}$ is the exponent showing the distribution of relaxation time $\tau_{P(AP)}$ for the P(AP) configuration.

The above expressions allow us to describe the results of experimental studies of TMC in MTJs, although they do not explain why two capacitances were chosen, while the magnetic field distribution diagram (Figure. 2) indicates in favor of three capacitances. The first of them is a capacitance whose parameters change very little when the MTJs electrodes are magnetized, and its value is determined by the design parameters of the MTJs and the dielectric characteristics of the barrier nanolayer. The second two capacitances are two microcapacitances in the interface region near each magnetic electrode. These capacitances are described by the DF model, and in the general case they have different values.

These capacitances appear because there is always a transitional inverse nanolayer between the metal tunnel contact and the barrier layer (dielectric or wide-gap semiconductor), the conductivity of which differs from the conductivity of the barrier layer. The dielectric characteristics and thickness of this transition nanolayer d_i $d_i \approx A_i\sqrt{\varepsilon_i\varepsilon_0(W_m - W_i)/(\gamma e^2 n_e)}$ are given by the contact potential difference $\Delta W_c = (W_m - W_i)$ which is determined by the values of the thermodynamic work function of an electron from the magnetic electrode material W_m and the barrier nanolayer material W_i. In most cases, the value is negative $\Delta W_c < 0$, and in such a non-equilibrium nanolayer becomes inverted, i.e. enriched with conduction electrons that pass from the magnetic electrode to the barrier layer. When an electric bias voltage is applied to the tunnel contact, the value of which is less than the contact potential difference, the thickness of the non-equilibrium inverted nanolayer near one metal electrode increases and near the opposite electrode decreases $d_{12} \approx A_i\sqrt{\varepsilon_i\varepsilon_0(W_c \pm U_i)/(\gamma e^2 n_e)}$ When the magnetic electrodes are magnetized and the MTJs transition from a state with a parallel orientation of magnetizations to a state with antiparallel magnetization of the electrodes, the dielectric characteristics and conductivity of such inverted nanolayers will change, and these changes, in our opinion, are the main cause of the TMR and TMC effects in MTJs.

As can be seen from the above scheme (Figure 2), in MTJs with antiparallel magnetization of electrodes in the inverted nanolayers of the barrier layer, an inhomogeneous magnetic field with a strong gradient of intensity arises. Such a magnetic field will lead to changes in the dielectric constant of the material ε due to magnetoelectric interaction. However, as already noted above, such changes in the value of ε cannot provide a significant change in resistance and capacitance, and cannot be considered as the main reason for the large values of TMC coefficients in MTJs.

We believe that the increase in resistance and decrease in capacitance of MTJs when switching from a state with parallel orientation of magnetizations to a state with antiparallel magnetization arises due to the non-equilibrium electric spin charge Q_S, which is formed in each inverted nanolayer. Such an electric charge Q_S arises in the inverted nanolayer due to the magnetically induced spatial separation of concentration of major $n_i(s_\uparrow)$ and minor $n_i(s_\downarrow)$ spin-polarized electrons. In the absence of a magnetic field gradient in each inverted nanolayer of MTJs, the relative concentration of major spin-polarized electrons $n_i(s_\uparrow)$ and minor spin-polarized electrons $n_i(s_\downarrow)$ in the inverted nanolayer d_i will be practically the same over the nanolayer thickness and close to their relative concentration in the magnetic electrode. In an inhomogeneous magnetic field, the electron is subjected to a magnetomotive force $\vec{F}(\vec{s})$ the absolute value of which is proportional to the magnetic field induction gradient $\nabla\vec{B}$ and the direction is given by the angle between the electron spin $\vec{\mu}_e$ and the magnetic field gradient

$$\vec{F}(\vec{s}) = \nabla(\vec{\mu}_e \cdot \vec{B}) \quad (3)$$

With antiparallel magnetization of MTJs, a strongly gradient magnetic field will lead to spatial separation in the inverted nanolayer of spin-polarized electrons and the formation of a non-equilibrium electric spin charge Q_S. The magnitude of the spin charge depends on the difference in the concentration of major $n_i(s_\uparrow)$ and minor $n_i(s_\downarrow)$ spin-polarized electrons in the magnetic electrode and is proportional to the magnetic induction gradient in the inverted layer d_i.

$$Q_s \approx A_s e[n(s_\uparrow) - n(s_\downarrow)]\mu_e \nabla B d_i, \quad (4)$$

where A_S is the proportionality coefficient.

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.

To estimate the maximum value of the non-equilibrium charge Q_0 and the potential difference U_i in the inverted nanolayer, as well as the additional spin-dependent capacitance C_S, we can use the condition of equality of the energy of the electrostatic interaction of the electron charge with the electric field of this capacitance W_e and the energy of the magnetic interaction W_μ of the electron spin μ_e with the magnetic field gradient $W_e = W_\mu$.

$$W_e = eU_i = eQ_0 C_s^{-1}$$
$$W_\mu = \mu_e \nabla B d_i \quad (5)$$

where $C_s \approx \varepsilon_i S / d_i$ ε_i is the dielectric constant of the barrier layer, S is the area of the magnetic electrodes, d_i is the thickness of the inverted nanolayer.

The magnitude of the non-equilibrium charge Q_0 and the magnitude of the compensation potential difference $U_{e\perp}$ in the $MTJ(\overrightarrow{M_1}\overrightarrow{M_2})$ with magnetic perpendicular anisotropy of the electrodes will be much larger compared to the similar non-equilibrium charge and the magnitude of the compensation potential difference $U_{e\|}$ in the $MTJ(M_{1\uparrow}M_{2\downarrow})$ with uniaxial magnetic anisotropy of the electrodes in the plane, because the magnetic field gradient in the $MTJ(\overrightarrow{M_1}\overrightarrow{M_2})$ is much larger than the magnetic field gradient in the $MTJ(M_{1\uparrow}M_{2\downarrow})$

$$U_{e\perp} \approx A_1 \mu_e \mu_i (H_1 + H_2) d_i / d_0$$
$$U_{e\|} \approx A_2 \mu_e \mu_i (H_1 + H_2) d_i / l_0 \quad (6)$$

where d_i is the thickness of the inverse nanolayer, H_1 and H_2 is the coercive force of the magnetic electrodes, d_0 and l_o is the thickness of the barrier layer and the transverse size of the magnetic electrode $l_o >> d_o$, A_1 and A_2 are the proportionality coefficients.

The resistance of MTJs with demagnetized electrodes R_T is determined by the dielectric characteristics and the thickness of the barrier layer, and is inversely proportional to the value of the transparency coefficient D_T of the barrier dielectric layer of the tunnel contact $R_T \sim (D_T)^{-1}$. The transparency coefficient of MTJs with demagnetized electrodes and the transparency coefficient of the MTJs with parallel magnetized electrodes at small values of the applied electric voltage can be written as $D_{\uparrow\uparrow}$

$$D_T = D_0 \exp[-\frac{2}{h} d_0 \sqrt{2m_e(U_0 - E_e)}]$$
$$D_{\uparrow\uparrow} = D_0 \exp[-\frac{2}{h} d_0 \sqrt{2m_e(U_{\uparrow\uparrow} - E_e)}] \quad (7)$$

where $E_e = eV < U_0$ and $E_e = eV < U_{\uparrow\uparrow}$ V and ; V is the applied electric voltage, U_0 and $U_{\uparrow\uparrow}$ is the energy height of the tunnel barrier for demagnetized and magnetized parallel magnetic electrodes, D_0 is a coefficient that depends on the electrical characteristics of the material of the electrodes and the barrier layer, h is the Planck constant, e and m_e is the charge and mass of the electron, d_0 is the thickness of the dielectric barrier layer.

It should be noted that in equation (7) there is an inequality between the energy height of the tunnel barrier $U_0 \neq U_{\uparrow\uparrow}$ for in $MTJ(M_{1\uparrow}M_{2\uparrow})$ with uniaxial magnetic anisotropy of the electrodes in the plane even with parallel magnetization of the electrodes. This difference arises due to the change in the dielectric characteristics of the barrier layer in the region of a strong magnetic field gradient near each of the electrodes due to magnetoelectric interaction. In $MTJ(\overrightarrow{M_1}\overrightarrow{M_2})$ with perpendicular magnetic anisotropy of the magnetic electrodes with parallel magnetization orientation, the magnetic field in the barrier layer is almost uniform. Therefore, the transparency coefficients and energy heights of the tunnel barrier in such MTJs should be the same with parallel magnetization of the electrodes and for the case when these electrodes are in a demagnetized state.

With antiparallel magnetization of the electrodes, the transparency coefficient will be smaller in magnitude both for $MTJ(M_{1\uparrow}M_{2\downarrow})$ with uniaxial magnetic anisotropy of the electrodes in the plane and for $MTJ(\overrightarrow{M_1}\overrightarrow{M_2})$ with magnetic perpendicular anisotropy of the electrodes. Such a decrease in the transparency coefficient is associated with the appearance of energy barriers that arise near each magnetic electrode. In the first approximation, with such a magnetization of the contacts, two additional barriers can be introduced. The first of them U_e is a Coulomb barrier, which is created due to the appearance of a non-equilibrium magnetically induced spin charge Q_s.

The second barrier U_e is a pseudo barrier, which describes the increase in resistance for spins of polarized electrons due to scattering on magnetic inhomogeneities in the region of the magnetic metal/dielectric interface of a positively charged electrode. The effective value of the thickness and energy height of such additional barriers will be less than the thickness and energy height of the dielectric barrier layer U_0, which determines the conductivity and the magnitude of the resistance during tunneling through the barrier dielectric layer of the MTJs with demagnetized electrodes $U_0 > U_s$ and $U_0 > U_e$; and $d_0 > d_s$, $d_0 > d_e$. The resistance of the tunnel contact with antiparallel magnetized electrodes can be represented as the sum of the tunnel resistances for each barrier $R_{\uparrow\downarrow} \approx R_0 + R_e + R_s$, where the magnitude of each term is determined by the magnitude of the corresponding barrier U_0, U_s and U_e.

At small values of the electric voltage V, when the electron energy is less than the height of such additional barriers, the transparency coefficient of the contact with antiparallel magnetized electrodes can be written as

$$D_{\uparrow\downarrow} = D_0 \exp\{-\frac{2}{h}[d_0\sqrt{2m_e(U_0 - E_e)} + d_e\sqrt{2m_e(U_e - E_e)} + d_s\sqrt{2m_e(U_s - E_e)}]\} \qquad (8)$$

The Coulomb barrier in the $MTJ(\overrightarrow{M_1}\overleftarrow{M_2})$ with magnetic perpendicular anisotropy of the electrodes $U_{e\perp}$ is likely to be higher compared to the Coulomb barrier in the $MTJ(M_{1\uparrow}M_{2\downarrow})$ with uniaxial magnetic anisotropy of the electrodes in the plane $U_{e||}$. which is associated with a large difference in the magnetic field gradients. The values of the barrier $U_{e|}$ in $MTJ(\overrightarrow{M_1}\overleftarrow{M_2})$ and in $MTJ(M_{1\uparrow}M_{2\downarrow})$ can be considered the same, and their magnitude depends mainly on the degree of spin polarization of electrons in the magnetic electrodes of MTJs.

As noted earlier, we believe that high values of TMC coefficients in MTJs are given by the presence of three consecutive capacitances: the capacitance of MTJs with demagnetized electrodes C_1 and two additional C_{i1} and C_{i2}, which are formed near each magnetic electrode. The total capacitance of MTJs is defined as $C_0^{-1} = C_1^{-1} + C_{i1}^{-1} + C_{i2}^{-1}$. In MTJs with parallel magnetized electrodes, the values of C_{i1} and C_{i2} are small and they have little effect on the value of the total capacitance. With antiparallel magnetization of the electrodes, the dielectric value of the additional capacitances C_{i1} and C_{i2} increases significantly due to the appearance of a magnetically induced spin charge Q_s in the inverted nanolayer. Majorly polarized electrons are concentrated in the yz–plane at the boundary of the inverted nanolayer with the magnetic electrode, and minorly polarized electrons are concentrated in the parallel yz–plane on 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. This approach differs from the case of some works [11,12]. where only one spin capacitance is introduced. Such two additional capacitances arise near each electrode in the magnetic contact/barrier nanolayer interface region. In the general case, their values are different, and their value changes when the magnetic contacts in MTJs are magnetized. The physical mechanism for changing the magnetoelectric capacitance is a change in the dielectric constant of the barrier nanolayer material in a non-uniform magnetic field, as well as the appearance of a non-equilibrium spin charge Q_s in the capacitance, which was discussed above. It is clear that in a homogeneous magnetic field, the dielectric constant of the barrier nanolayer material and the formation of a non-equilibrium spin charge Q_s do not occur.

The contribution of the non-equilibrium electric spin charge Q_s to the additional capacitances C_{i1} and C_{i2}, in our opinion, is the reason why the total capacitance of MTJs with antiparallel magnetized electrodes $C_{0\uparrow\downarrow}$ is smaller than the capacitance of MTJs with parallel magnetized electrodes $C_{0\uparrow\uparrow}$. Based on the results of, we believe that the total capacitance of tunnel contacts with antiparallel magnetized electrodes $C_{0\uparrow\downarrow}(\omega,V)$ can be represented in a first approximation, through three series capacitances: the capacitance $C_{AP}(\omega,V)$ and two complex spin capacitances $C_{s1}(\omega,V)$ and $C_{s1}(\omega,V)$, where $C_{s1}(\omega,V) \approx C_{s2}(\omega,V)$

$$[C_{0\uparrow\downarrow}(\omega,V)]^{-1} = [C_{AP}(\omega,V)]^{-1} + [C_{s1}(\omega,V)]^{-1} + [C_{s2}(\omega,V)]^{-1} \qquad (9)$$

Here $C_{si}(\omega,V) = C_{s0}(V) + \frac{G_{si}}{j\omega}$, G_{si} is the conductivity of the barrier layer in the inversion region [5,11].

Taking into account formula (1), we can obtain an expression for estimating the spin capacitance $C_{s0}(M_{1\uparrow}M_{2\downarrow},V)$ *for* $MTJ(M_{1\uparrow}M_{2\downarrow})$ with uniaxial anisotropy of electrodes and the spin capacitance $C_{s0}(\overrightarrow{M_1}\overleftarrow{M_2},V)$ for $MTJ(\overrightarrow{M_1}\overleftarrow{M_2})$ with perpendicular anisotropy of electrodes

$$C_{s0}(M_{1\uparrow}M_{2\downarrow},V) \approx A_2\frac{eS[n_i(s_\uparrow) - n_i(s_\downarrow)]\mu_e\mu_i(H_1+H_2)}{l_0 d_i\,|V|}$$
$$C_{s0}(\overrightarrow{M_1}\overleftarrow{M_2},V) \approx A_1\frac{eS[n_i(s_\uparrow) - n_i(s_\downarrow)]\mu_e\mu_i(H_1+H_2)}{d_0 d_i\,|V|} \qquad (10)$$

Here S is the area of magnetic electrodes, d_i is the thickness of the inverse nanolayer. d_0 and l_0 is the thickness of the barrier nanolayer and the transverse size of the magnetic electrode, A_1 and A_2 are the proportionality coefficients.

The Influence of Temperature and Electric Current on the Characteristics of MTJs

Even a brief overview of the mechanisms of the TMR and TMC effects in MTJs shows that with increasing temperature, the values of the TMR and TMC coefficients should decrease. Literature data of experimental studies show that the values of the TMR coefficients decrease with increasing temperature and current through MTJs [13]. There is very little experimental data on the change in the values of the TMC coefficients, although it is clear that with increasing temperature, the values of the TMC coefficients should also decrease. The decrease in the TMR and TMC coefficients should lead to a decrease in the degree of electron polarization conductivity in magnetic electrodes and lowering the energy height of the barrier nanolayer parameters in MTJs. But for practical use of the TMR and TMC effects in MTJs, it is necessary to know the magnitude and temperature range of changes in the characteristics of MTJs. Therefore, we conducted an experimental study of the effect of temperature on the TMR and TMC coefficients of our MTJs (Figure. 3).

The measurement results (Figure. 3) showed that the resistance and capacitance of our MTJs with parallel magnetization of the magnetic electrodes change with temperature less than with their antiparallel magnetization, and the value of the TMR coefficients decreases with temperature more strongly than the value of the TMC coefficients. Moreover, in the $Tb_{22}Co_5Fe_{73}$/Pr_6O_{11}/$Tb_{19}Co_5Fe_{76}$ MTJs, the relative changes in the value of the TMR and TMC coefficients with increasing temperature change more than in the $Co_{80}Fe_{20}$/Pr_6O_{11}/$Co_{30}Fe_{70}$MTJs.

We believe that the weaker temperature dependence of the resistance and capacitance of MTJs with parallel magnetization of the magnetic electrodes compared to the similar dependence with their antiparallel magnetization is explained by the difference in the value and temperature dependence of the energy barrier for these two cases. In the first case, the energy barrier value is determined by the thickness and dielectric characteristics of the barrier nanolayer material. With antiparallel magnetization of the electrodes, the effective value of the energy barrier is larger and is determined by the sum of two energy barriers: the energy barrier with parallel magnetization of the magnetic electrodes and the energy barrier created in MTJs due to the spin charge, which we discussed earlier. The effective value of the value of such a spin barrier will decrease with increasing temperature much more than the decrease in the value of the dielectric energy barrier. Therefore, the resistance and capacitance values of MTJs with antiparallel magnetized electrodes should approach the resistance and capacitance values of MTJs with parallel magnetized electrodes with increasing temperature.

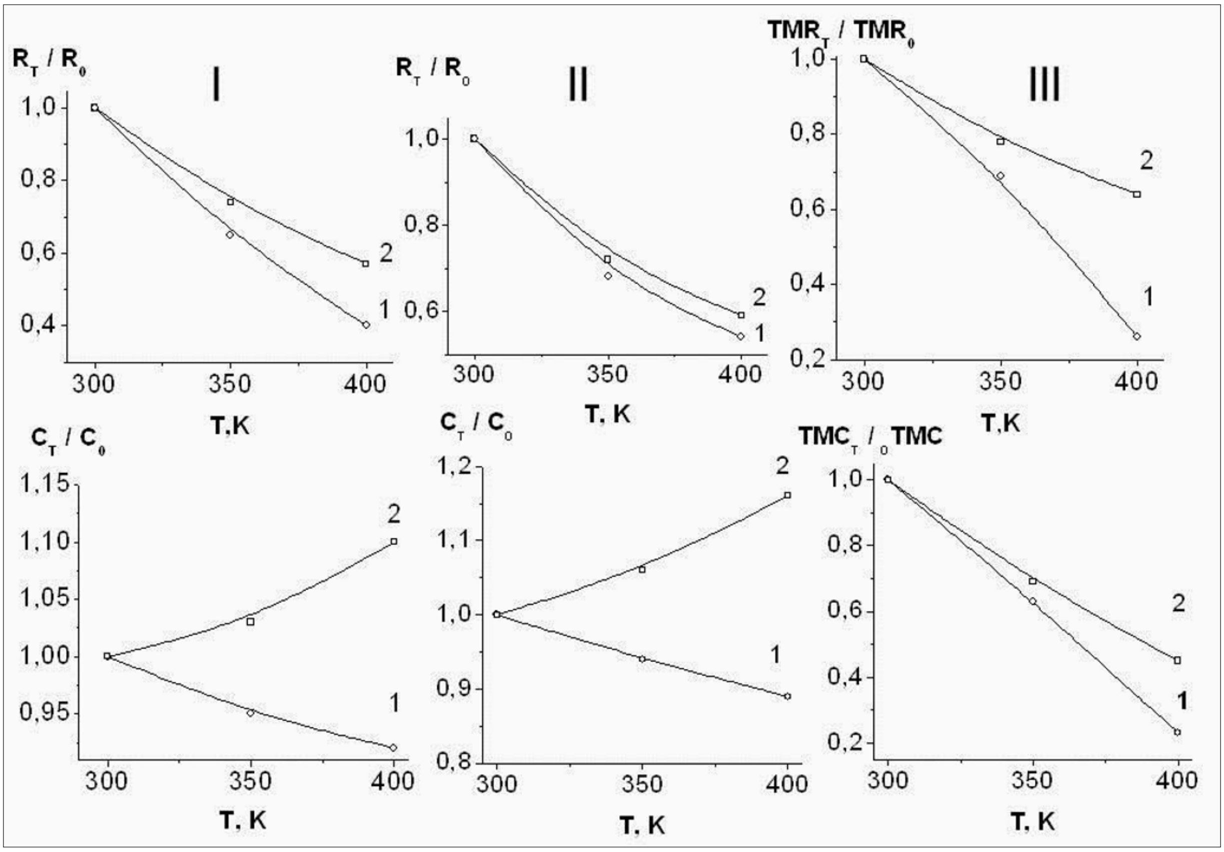

Figure 3: Change in the resistance, capacitance, and tunnel magnetoresistance and tunnel magnetocapacitance coefficients with temperature. I - MTJs $Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_{76}$: 1 - antiparallel magnetization of the electrodes, 2 - parallel magnetization of the electrodes; II - MTJs $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$: 1 - antiparallel magnetization of the electrodes, 2 - parallel magnetization of the electrodes; III - TMR and TMC values: I - MTJs $Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_{76}$, II - MTJs $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$

High-frequency recording and rewriting of information is one of the key requirements for information recording and processing systems. Therefore, these issues are also extremely relevant for information carriers based on MTJs. Today, several methods of recording and rewriting information in MTJs are considered the most promising. This is the magnetization reversal of the MTJs control magnetic electrode by the magnetic field of the injected spin-polarized current, or by the current field through special electrodes, as well as the magnetization reversal of one of the electrodes also due to the electrically controlled magnetic anisotropy [15-18]. All these methods have been experimentally verified, but unfortunately, the impact of multiple cycles of recording and rewriting information on the technical characteristics of MTJs has not been measured. However, even for a single implementation of recording and rewriting information, it is necessary to apply sufficiently powerful electrical pulses. With repeated repetition, such pulses can lead to changes in the values of TMR and TMC in MTJs. Therefore, we have conducted a study of the impact of the number of nanosecond current pulses of different magnitude on the value of the TMR and TMC coefficients in our MTJs.

The measurement results showed that the values of the TMR and TMC coefficients in our MTJs at a very small amplitude of the current pulse $J \leq 10^{-6}$ A practically do not change. With an increase in the amplitude of the current pulse (Figure. 4), the values of the TMR and TMC coefficients after a certain number of pulses pass through the MTJs decrease. Moreover, with an increase in the current amplitude, the values of the TMR and TMC coefficients decrease much more, and at large values of the current amplitude $J \geq 5\times10^{-3}$A and the current density through the MTJs $j \geq 10^4$ *A/cm2*, the values of the TMR and TMC coefficients decrease significantly even after the passage of a single current pulse. It should also be noted that the values of the TMC coefficients in MTJs after the action of electric pulses change less than the values of the TMR coefficients.

Such changes in the values of the TMR and TMC coefficients after the passage of electric pulses with a high current density suggest that under the action of the electric field and current in MTJs at the interfaces of the constituent materials, stimulated diffusion of atoms occurs, which can lead to blurring and the appearance of inhomogeneity of conductivity through the interface, which causes a decrease in the values of the TMR and TMC coefficients in MTJs. The results of the conducted studies show that although MTJs are promising elements for creating magnetic information carriers, in practical developments it is necessary to take into account the possible deterioration of the technical characteristics of this type of media during multiple recording and rewriting of information.

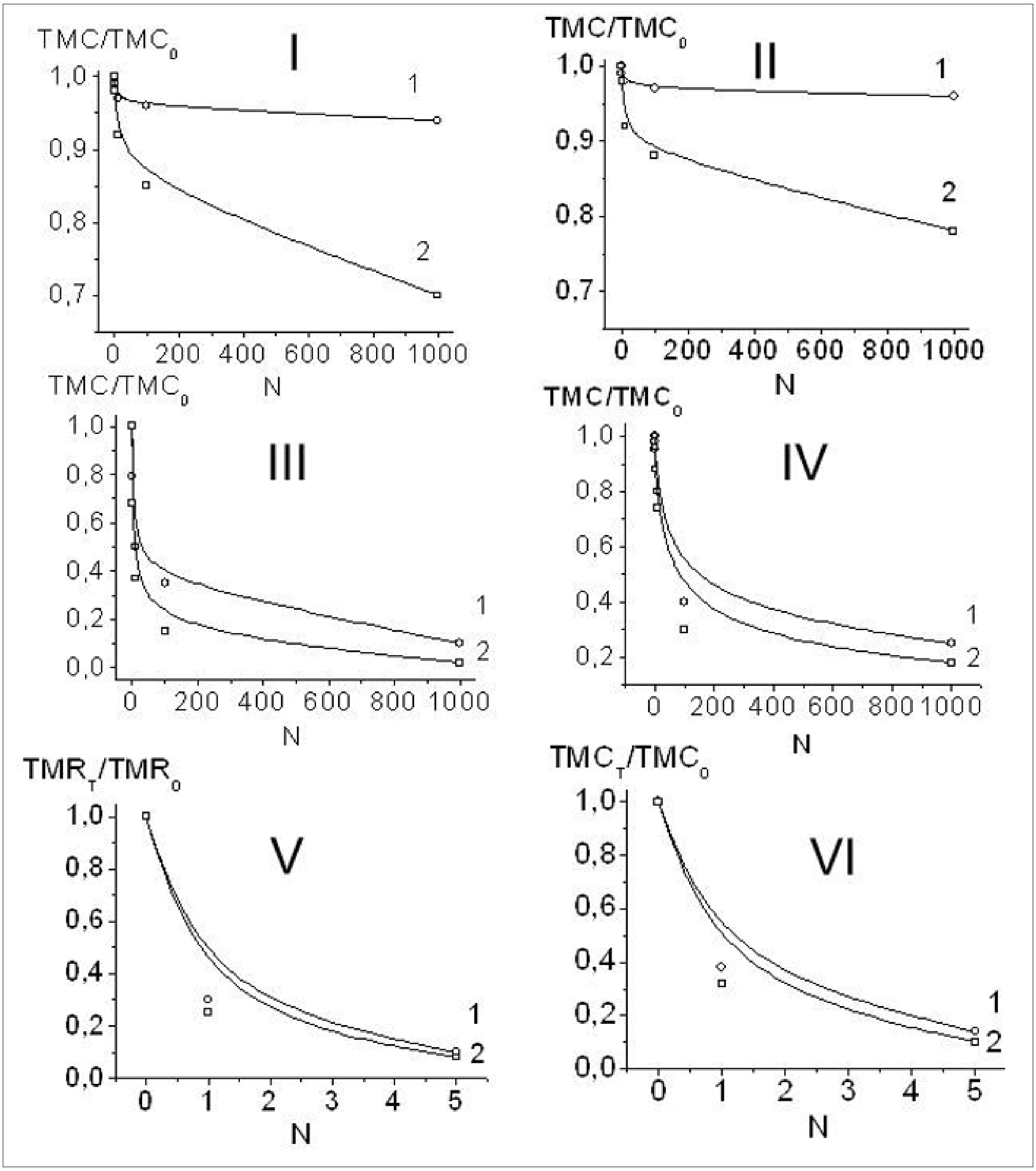

Figure 4: Change in the value of the coefficients TMR (I, III, V) and TMC (II, IV,VI) after the passage of N current pulses with different current amplitude J for a duration of $\tau \approx 20$ ns: I and II – $J=5\times10^{-5}$A; III and IV – $J=5\times10^{-4}$ A; V and VI – $J=5\times10^{-3}$ A. 1 – MTJs $Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_{76}$, 2 – MTJs $Co_{80}Fe_{20}/Pr_6O_{11}/Co_0Fe_{70}$.

Such changes in the values of the TMR and TMC coefficients after the passage of electric pulses with a high current density suggest that under the action of the electric field and current in MTJs at the interfaces of the constituent materials, stimulated diffusion of atoms occurs, which can lead to blurring and the appearance of inhomogeneity of conductivity through the interface, which causes a decrease in the values of the TMR and TMC coefficients in MTJs. The results of the conducted studies show that although MTJs are promising elements for creating magnetic information carriers, in practical developments it is necessary to take into account the possible deterioration of the technical characteristics of this type of media during multiple recording and rewriting of information.

The simplest type of such an information carrier can consist of memory cells, which are essentially double MTJs in design, in which one of the magnetic electrodes is common (Figure 5). This common magnetic electrode is magnetized when writing information to a given memory cell.

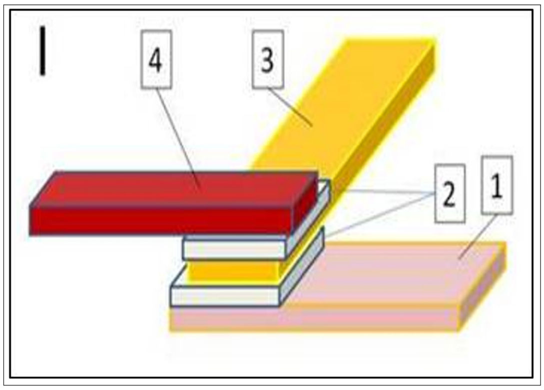

Figure 5: Scheme of the information carrier based on the MTJs: 1 – magnetic electrodes with a fixed direction of magnetization and coercive force H_1, 2 – dielectric barrier layer, 3 – magnetic electrode with a small coercive force H_3, 4 – magnetic electrodes with a fixed direction of magnetization and coercive force *H4*.

Magnetic electrodes 1, 3 and 4 have different values of coercive force H1>H4>>H3, which allows to pre-magnetize magnetic electrodes 1 and 4 in antiparallel directions with an external magnetic field. Information recording with such a carrier design is easiest to perform with a spin current. When recording "1", a powerful recording pulse JW is applied to magnetic electrodes 1 and 3, where on the magnetic layer 3, which has a low coercive force and is magnetized during recording. Moreover, a negative electric field voltage is applied to electrode 1. When recording "0", a powerful recording pulse JW is applied to magnetic electrodes 4 and 3 and a negative electric field voltage is applied to electrode 4. The amplitude of the writing pulse is determined by the magnitude of the current JW, which must be passed through the tunnel contact to obtain a local magnetization reversal of the magnetic electrode 3, (11) where Ha is the magnitude of the magnetic anisotropy field of the electrode 3, Se and h are the area and thickness of the magnetic electrode 3, μ and τs are the magnetic permeability and the relaxation time of the spin polarization in the material of this electrode, $\gamma < 1$ is the coefficient characterizing the magnitude of the spin polarization in the magnetic materials of the electrodes 1 or 4, e is the electron charge, μ 0 is the absolute magnetic permeability.

When reading information on 2 pairs of electrodes 1-3 and 4-3, 2 identical reading pulses JR are simultaneously applied to 2 pairs of electrodes 1-3 and 4-3, where a positive field voltage is applied to electrode 3. The amplitude of the read pulse is much smaller than the amplitude of the write pulse JR < 0.01JW. Registration of the information recorded in the ml memory cell ("0" or "1") can be carried out 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, i.e. the TMR effect is used, and in the second case the TMC effect is used. The magnitude of the phase shift between the read pulses will be determined by the difference in the capacitance between the two pairs of magnetic electrodes 1-3 and 4-3 $\Delta\phi = f(C_{13} - C_{43})$. If "1" is recorded in the memory cell, then the capacitance between the contacts C13 will be greater than the capacitance C_{43} $C_{13} > C_{43}$. When "0" is recorded in the memory cell, then $C_{13} < C_{43}$. 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.

Experimental studies show that to reverse the magnetization of the magnetic electrode of MTJs by a spin current, it is necessary to pass a current with a high density j = 104-106 A/cm2 through MTJs. An electric current of such a density, as shown by the results of this work, can lead to a significant reduction in the technical characteristics of spintronics elements, the principle of operation of which is based on the TMR and TMC effects in MTJs.

Magnetization reversal of one of the electrodes due to electrically controlled magnetic anisotropy not only makes the technological and structural scheme of a magnetic information carrier based on MTJs more complex, but also creates a rather high electric field in MTJs with E >103 V/cm, which can also affect the magnitude of the TMR and TMC coefficients in MTJs. One of the most promising ways to reduce this effect is the use of very short (picosecond) electrical pulses, which requires additional research [19,20].

Conclusion

The results of this work show that the changes in the resistance and capacitance of MTJs and the large values of the TMR and TMC coefficients are due to the spatial separation of electrons with major s↑ and minor s↓ polarization and the appearance of a non-equilibrium spin charge in the magnetic electrode/barrier nanolayer interface region with antiparallel magnetization of the magnetic electrodes in MTJs. The values of the TMR and TMC coefficients in MTJs decrease with increasing temperature and, what is especially important, these coefficients decrease significantly after the passage of current pulses with a high current density through MTJs. The reason for such a decrease in the TMR and TMC coefficients in MTJs may be stimulated diffusion of atoms, which leads to the blurring of the magnetic electrode/barrier nanolayer interface and the appearance of conductivity inhomogeneities in it. All this shows that although MTJs are considered as basic elements for creating information carriers, for this practical effect of the transition from the stage of scientific research to the stage of creating prototypes and manufacturing products, it is necessary to carry out not only the development of design and technological documentation, but also to establish the main factors that affect the technical characteristics of the samples and their thermal and temporal stability. The desire to draw the attention of scientists to the noted problems and tasks was one of the tasks of this work.

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