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

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Introduction

The Although studies of the characteristics of magnetic tunnel junctions (MTJs) have been studied for a long time, the prospect of such structures as basic elements of spintronics began to be discussed after a large change in resistance under the influence of a magnetic field was obtained in them. This effect was called tunnel magnetoresistance (TMR), and its value in the best samples reached a value of up to 500%. Recently, in magnetic tunnel contacts, the effect of changing the capacity during remagnetization of one of the magnetic electrodes, which is called the tunnel magnetic capacity (TMC), has been registered. The effect of tunnel magnetic capacitance is intensively studied, although today there are already talks about a good prospect of its practical use. The results of experimental studies show that the value of the tunnel magnetic capacitance, as well as the value of the tunnel magnetic resistance, depend not only on the value of the spin polarization of the magnetic electrodes, but also strongly depend on the material and structure of the magnetic metal/insulator interface. Record high values of TMC and TMR were obtained in MTJ, in of which magnesium oxide is used as an insulator. In Fe/MgO/Fe tunnel contacts, the value of TMC reaches values of more than 400%, and the value of TMR can be even greater than TMR>500%. Such high values of TMR and TMC can be obtained only with a very good agreement between the crystal lattice of the barrier nanolayer and the crystal lattice of the magnetic electrode. All this greatly complicates the technology of manufacturing tunnel magnetic electrodes and narrows the operating temperature range of spintronics elements based on them.

In this work, we want to present the results of our research on the effects of changing resistance and capacitance in magnetic tunnel contacts, in which the magnetic electrodes have perpendicular anisotropy, to show that high TMC and TMR values can be obtained in such tunnel contacts. The paper proposes a mechanism that explains the appearance of tunnel magnetic capacitance in magnetic tunnel contacts with electrodes that have perpendicular anisotropy, presents the results of measurements of the value of tunnel magnetic resistance and tunnel magnetic capacity in tunnel contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$, where the value of tunnel magnetic resistance is almost 120%, and the value of the tunnel magnetic capacity is more than 110%and provides a scheme for constructing a spin information carrier based on the TMC effect. We want to show that tunnel magnetic contacts with perpendicular magnetization of electrodes can have a good prospect of practical use in the development of spintronics elements.

A feature of tunnel magnetic contacts with perpendicular magnetization of the electrodes is a strong change in the configuration and direction of the magnetic field in the barrier layer during the transition from the variant with parallel magnetization to the antiparallel magnetization of the magnetic electrodes. With parallel magnetization of the electrodes in the tunnel contact, there is an almost uniform magnetic field in the barrier layer. When the electrodes are antiparallel magnetized, a very strong magnetic field gradient is formed near each electrode in the barrier layer. Moreover, the strongest changes in the intensity of the magnetic field (the magnetic field **H** is directed in the *x)* in the direction parallel to the direction of magnetization of the magnetic electrodes *dH/dx>>dH/dy* and *dH/dx>>dH/dz*.

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

$d_i \approx A_i\sqrt{(\varepsilon_i\varepsilon_0 W_c)/(\gamma e^2 n_e)}$ Where $n_e$is the concentration of conduction electrons in the magnetic electrodes, e is the electron charge, $\varepsilon_i$is the dielectric constant of the barrier layer, ε_0 is the absolute dielectric constant, γ is the coefficient that characterizes the transition of conduction electrons from the magnetic electrode to the barrier layer, A is the proportionality coefficient.

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

The electric field of the nonequilibrium spin charge opposes the magnetomotive force, which limits the maximum value of the charge value.. Therefore, the conductivity and capacity of the tunnel contact with parallel magnetized electrodes will be determined with great accuracy by the characteristics of the passage of electrons through the barrier dielectric layer. At low values of the applied electric voltage , when the electron energy is much lower than the energy height of the tunnel barrier U_0 $E_e = eV < U_0$ the transparency coefficient of the tunnel contact with parallel magnetized electrodes can be written as $D_{\uparrow\uparrow} = D_0\exp[-\frac{2}{h}d_0\sqrt{2m_e(U_0-E_e)}]$, In tunnel contacts with antiparallel magnetized electrodes, the conductivity will depend on the tunnel characteristics of electrons through the dielectric barrier U_0 and through additional energy barriers that arise in such contacts near each magnetic electrode. The main barrier U_0 determines the conductivity and the amount of resistance when electron tunneling through the barrier dielectric layer, and as well two additional barriers. The first of them U_e is the Coulomb barrier, which is created due to the appearance of a non-equilibrium magnetically induced spin charge . The second barrier U_s is a pseudo-barrier , which describes the passage of spin polarized electrons and introduces additional resistance into the overall conductivity of tunnel contacts with antiparallel magnetized electrodes. It is clear that the effective thickness and energy height of pin-dependent and Coulomb barrier are significantly smaller than the analogous parameters of the dielectric barrier layer. At low values of the applied electric voltage V, when the electron energy is less than the energy height of the Coulomb barrier $E_e = eV < U_e$ the transparency coefficient of the tunnel contact with antiparallel magnetized electrodes can be written as

$D_{\uparrow\downarrow} = D_0 e^{-\frac{2}{h}d_0\sqrt{2m_e(U_0-E_e)}} e^{-\frac{2}{h}d_e\sqrt{2m_e(U_e-E_e)}} e^{-\frac{2}{h}d_s\sqrt{2m_e(U_s-E_e)}}$ Here h is the Planck constant, is the mass of the electron, $d_0$is the thickness of the dielectric barrier layer, $d_e$is the effective thickness of the Coulomb barrier, d_s is the effective thickness of the spin-dependent barrier, D_0 is the coefficient that depends on the material of the electrodes and the barrier layer.

In experimental studies, we used tunnel contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$. For the manufacture of tunnel contacts with perpendicular anisotropy of magnetic electrodes, we used films produced by magnetron sputtering of $Tb_{22}Co_5Fe_{73}$ and $Tb_{19}Co_5Fe_{76}$ alloy targets. We measured tunnel magnetocapacitance and magnetoresistance in high-resistance $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ contacts using a measuring bridge and the four-probe method. The measurement results are presented in Figure 1.

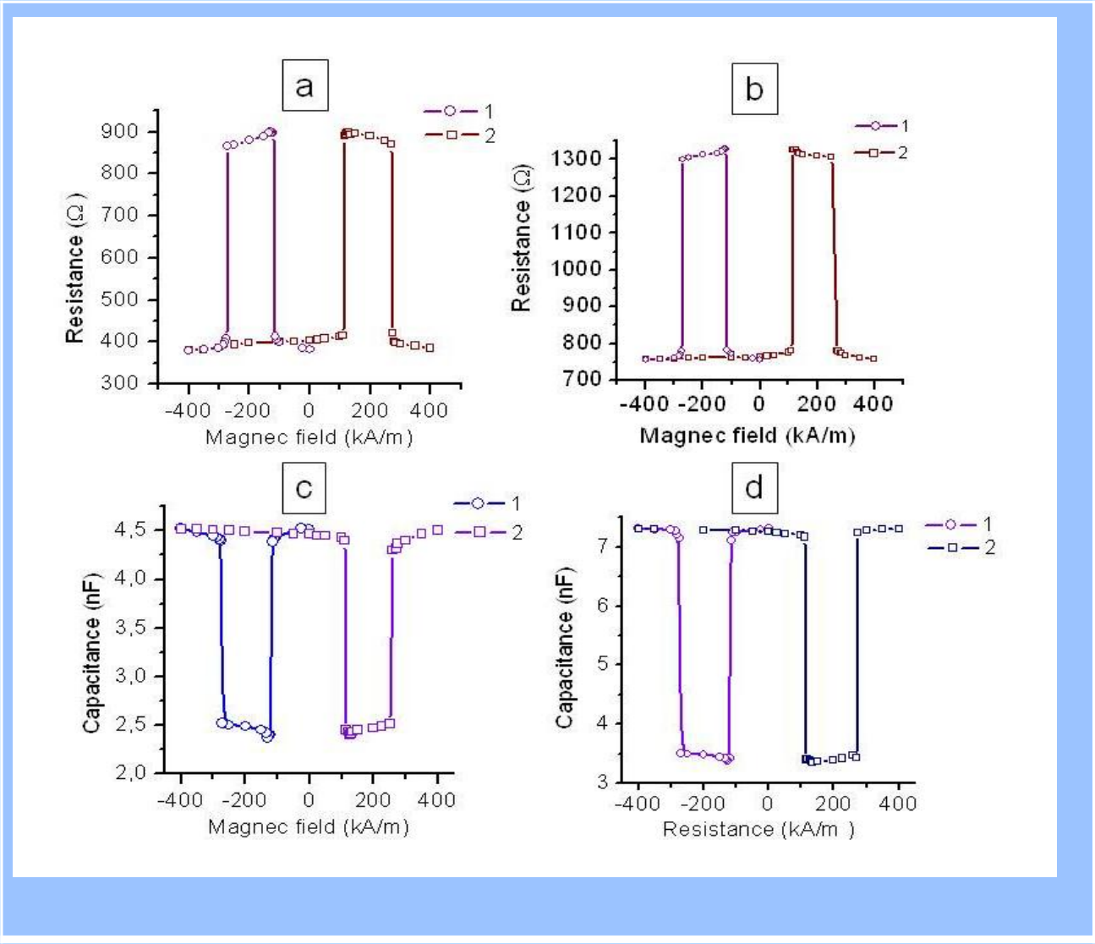

Fig. 1. *kA/*Change in resistance and capacitance of parallel magnetized tunnel contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ with different thickness *d* of the barrier layer depending on the direction and magnitude of the permanent magnetic field: (a) and (c) - are curves for contact with thickness of the barrier layer $d_1=1-1,2$ *nm*, (b) and (d) are curves for contact with the thickness of the barrier layer $d_2=1.5-1.8$ *nm*. The curve 1 describes the process when the magnetic field changes from *H=0* to *H= –400 kA/m*, the curve 2 describes the process when the magnetic field changes from *H= –400 kA*/m to *H= +400 kA/m*.

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

Magnetocapacitance and information recording

It is clear that for the practical use of tunnel magnetocapacitance and magnetoresistance in tunnel contacts with perpendicular magnetization of electrodes, it is necessary to conduct detailed experimental and technological developments. However, we would like to propose in this work the principle of recording information and the scheme of building an information carrier based on tunnel magnetocapacitance and magnetoresistance in tunnel contacts (Fig. 2).

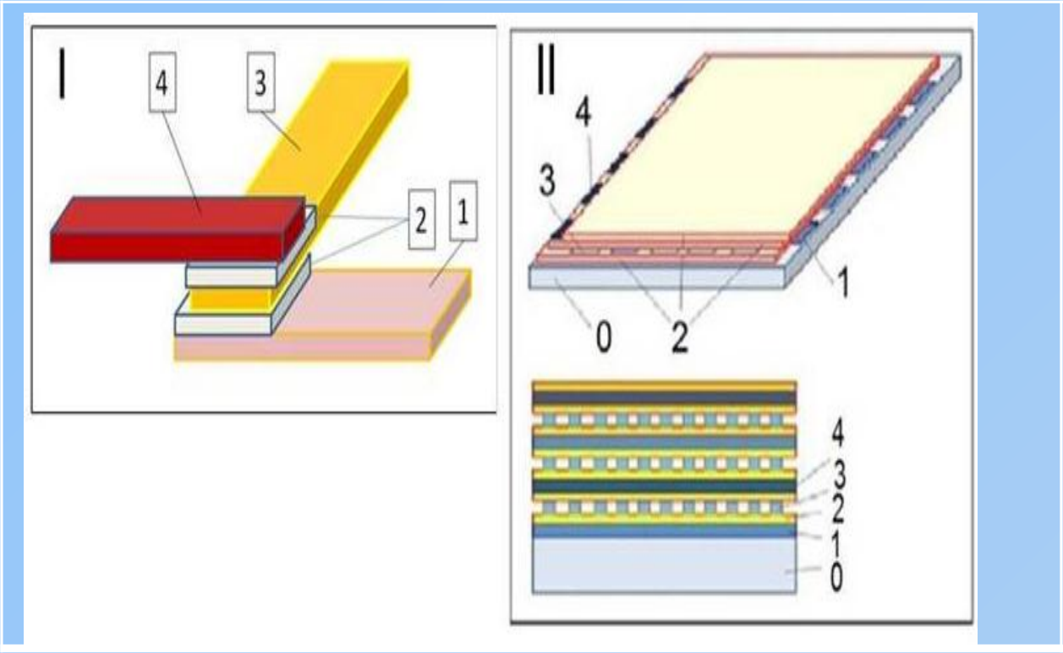

Fig. 2. Scheme of the information carrier based on the tunnel magnetocapacitance in tunnel contacts with perpendicular magnetization of the electrodes: 0 – substrate of the information carrier, 1 and 4 – magnetic electrodes with a fixed direction of magnetization, 2 – dielectric barrier nanolayer, 3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

The magnetic spin information carrier consists of a substrate 0, on which a highly coercive magnetic layer 1 is applied, the material of which has a high spin polarization of electrons and perpendicular anisotropy. Structurally, layer 1 is made in the form of a system of *m* separated flat electrodes with a thickness of several tens nanometers and a width of about one micron. A continuous dielectric barrier nanolayer 2 with a thickness of *1-3* nanometers made of a dielectric non-magnetic material is applied to the magnetic layer 1. A magnetic layer 3 is applied to the barrier nanolayer, which also has a high electron spin polarization and perpendicular anisotropy, but a small coercive force H_3 compared to the coercive force H_1 of the magnetic layer 1 H_3~0,1H_1. These flat electrodes are oriented perpendicular to the m flat electrodes of magnetic layer 1. A similar dielectric barrier nanolayer 2 is deposited on magnetic layer 3, and a magnetic layer 4 is deposited on it, the material of which also has high electron spin polarization and perpendicular anisotropy, but its coercive force is much greater even than the coercive force of the magnetic layer 1 $H_4 > H_1$. The design of the electrodes of the magnetic layer 4 is the same as in the magnetic layer 1. Then, layer 5 can be successively deposited on layer 5 with nanolayer 2, layer 3, nanolayer 2, layer 1, etc. Recording of information on the described tunnel spin carrier is carried out in the following way. Before recording information, magnetization is carried out in the constant magnetic field of magnetic electrodes 1 and 4. The constant magnetic field is applied to the medium, the intensity of which is perpendicular to the plane of magnetic electrodes 1 and 4 and the magnitude of the field intensity H_0 exceeds the coercive force H_4 of the magnetic layer 4 $H_0>H_4$. Then an oppositely directed magnetic is applied to the carrier, the intensity of which H_{01} exceeds the coercive force H_1 of the magnetic layer 1, but is significantly less than the coercive force H_4 of the magnetic layer 4 $H_4>>H_{01}>H_1$. When writing "1" to the *ml* memory cell, a powerful recording pulse J_W is applied to the *m* flat electrode of magnetic layer 1 and the *l* flat electrode of magnetic layer 3. Moreover, the electric field voltage to the *m* electrode of layer 1 is negative in relation to the *l* electrode of layer 3. When writing "0" in the *ml* memory cell, the same powerful recording pulse J_W is applied to the *m* flat electrode of magnetic layer 4 and the *l* flat electrode of magnetic layer 3. The amplitude of the write pulse J_W is determined by the amount of current that must be passed through the tunnel contact to obtain a local remagnetization of *l* flat electrode of magnetic layer 3 in the *ml* memory cell $J_W > \frac{H_a 4\pi\mu_0 S_e h e}{\gamma\tau_s\mu_B\mu}$,

where $J_W$is the magnitude of the current through the contact, S_e and *h* is area and thickness of the magnetic electrode 3 in the *ml* memory cell, μ and τ_s is magnetic permeability and spin polarization relaxation time in the material of the magnetic layer 3, $\gamma<1$ is the coefficient characterizing the value of spin polarization in magnetic materials of magnetic layers 1 or 5, *e* is electron charge, μ_0 is absolute magnetic permeability. When reading information from any *ml* memory cell, two identical reading pulses J_R are sent simultaneously to the *m* electrode of magnetic layer 1 and the *m* electrode of magnetic layer 4. The amplitude of the reading pulse J_R is much smaller than the amplitude of the writing pulse $J_R<<0,1J_W$, and the polarity of such a pulse coincides with the polarity of the recording pulses. Then, with the help of the processing unit, the phase difference between the two pulses that passed through the *ml* tunnel contact 1-2-3 between magnetic layers 1 and 3 and the pulse that passed through the *ml* tunnel contact 4-2-3 between magnetic layers is recorded 4 and 3. The magnitude of the phase shift between the reading pulses will depend on the difference in capacitance between tunnel magnetic contacts 1-2-3 and 4-2-3 $\Delta\Phi=f(C_{13}-C_{43})$. The capacity of these contacts will vary depending on the mutual orientation of magnetization of magnetic electrodes 1 and 3 or 4 and 3 in the *ml* memory cell. If "1" is written in the *ml* memory cell, then the capacity between contacts 1-2-3 will be greater than the capacity of contacts 4-2-3 $C_{13}>C_{43}$. When "0" is written in the *ml* memory cell, the capacity between contacts 1-2-3 will be less than the capacity of contacts 4-2-3 $C_{13}<C_{43}$. The method of measuring the phase difference between signals is much more sensitive compared to the method of measuring the difference of amplitudes between these signals, which makes it possible to obtain high sensitivity and reliability of reading information from the described spin media.