Information Recording Medium Based on Tunnel Magnetic Junctions

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INTRODUCTION

Today, tunneling magnetic junctions (MTJs) are considered 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, in which record-breaking values of tunnel magnetoresistance (TMR) and tunnel magnetocapacitance (TMC) were obtained in MTJs, where the TMC value reaches values of more than 400%, and the TMR value can be more than 500%. However, the high values of internal resistance and the complexity of switching the conductivity of microelements based on MTJs make it difficult to use them as control elements in spintronics microcircuits, and they are also not very suitable due to their low sensitivity for measuring the magnetic field.

Our analysis of the possibility of practical use shows that the prospect of practical use of MTJs is associated with the development of information recording media based on them. This statement is based on the fact that MTJ-based data carriers allow not only quickly recording the necessary information at high speed, but also providing high reliability of its preservation and protection. Unlike carriers based on semiconductor chips, MTJ-based data carriers will have high temperature, radio electronic and radiation resistance and to erase the information recorded in them, it is necessary to apply a sufficiently strong magnetic field, or to apply powerful pulses of spin-polarized current to the recording electrodes. Therefore, spin data carriers have the prospect of widespread use in special small-sized moving objects and systems.

Record-high TMC and TMR values are achieved in MTJs of the Fe/MgO/Fe type only with very good matching between the crystal lattice of the magnetic electrode and the crystal lattice of the barrier nanolayer. Such an ideal matching of the lattice structure is achieved when using epitaxial methods for manufacturing MTJs, which complicates the production technology. However, even with the initial matching of these lattices in MTJs during operation, temperature stresses will arise in the interface region, which can greatly reduce the TMC and TMR values in them.

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.

The results of theoretical works and our experimental studies of the interaction of samarium cobalt magnets allow us to present a scheme of magnetic interaction and magnetic field distribution in the MTJ with parallel and antiparallel magnetized magnetic electrodes (Fig.1).

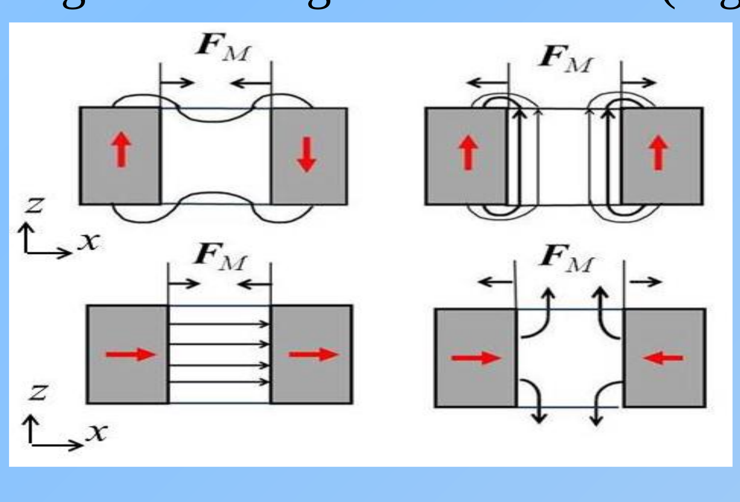

Fig. 1. Scheme of the configuration of magnetic field and magnetic interaction between magnetic electrodes of MTJ with different anisotropy of electrodes: uniaxial anisotropy in electrode plane MTJ($M_{1\uparrow}M_{2\uparrow}$) and MTJ($M_{1\uparrow}M_{2\downarrow}$)-(top); and perpendicular anisotropy MTJ($\overrightarrow{M_1}\overrightarrow{M_2}$) and MTJ($\overrightarrow{M_1}\overleftarrow{M_2}$) - (bottom).

As shown in Fig. 1 (top) in MTJ with parallel orientation of the magnetizations of the electrodes, which coincides with the direction of the *z* axis, a magnetic repulsive force acts between the electrodes along the *x* axis. In the insulating barrier layer with such orientation of the magnetizations MTJ near each magnetic electrode a magnetic field gradient arises, which is directed along the *x* axis. Along the *z* axes the magnetic field strength $H=H_z$ changes much weaker and practically not change along the *y* axis: |dHz/dx|>>|dHz/dz|>|dHz/dy|. With antiparallel magnetization of the magnetic electrodes in MTJbetween them an attractive force acts along the *x* axis. The magnetic field in the barrier layer changes not only along the *x* axis, but also changes 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 at parallel orientation of electrodes MTJ an attractive force acts between the magnetic electrodes, which is directed along the *x* axis. In the insulating barrier layer, with such an orientation of the magnetizations, a practically uniform magnetic field $H=H_x$ acts along the *x* axis. The strength of this magnetic field is close in magnitude to the perpendicular anisotropy of the magnetic electrodes $H_x \approx H_a$. Therefore, it can be assumed that in the barrier layer of such MTJ dHx/dx|≥|dHx/dz|~|dHx/dy|~0. With antiparallel magnetization of the electrodes in the MTJ, a repulsive force acts between the magnetic electrodes along the *x* axis. In the insulating barrier layer, a strong magnetic field gradient appears along the *x* direction.

The absolute value of the magnetic field strength decreases from the maximum value $H_o \approx H_a$ 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: dHx/dx|>>|dHx/dz|≥|dHx/dy|. The inhomogeneity and strong magnetic field gradient in the nonmagnetic barrier layer of the MTJ can not only lead to changes in its dielectric characteristics, but can also cause spatial separation of major and minor spin-polarized electrons in the region of the interface metal magnetic electrode/dielectric barrier layer. In the absence of a magnetic field and even in a uniform magnetic field in In the MTJ barrier layer, a transition nanolayer is formed under the action of the electric field of the contact difference of potential.

A strongly gradient magnetic field in the barrier nonmagnetic layer of the MTJ can lead to spatial separation of major and minor spin-polarized electrons in the inverted nanolayer d_i. The magnetomotive force in this case is not zero and its interaction with major and minor spin-polarized electrons has the opposite direction, which leads to the spatial separation of these electrons in the inverted nanolayer. 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 and a non-equilibrium electric charge is formed in it. The electric field of the non-equilibrium spin charge counteracts the magnetomotive force, which limits the maximum value of the charge . The magnetically induced force of a strongly inhomogeneous field in the MTJ with with antiparallel magnetized electrodes and perpendicular anisotropy will lead to the spatial separation of major and minor polarized electrons in the inverted nanolayer .

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, between the boundaries inverted nanolayer, a potential difference arises, which allows us to consider this inverted nanolayer as an additional spin-dependent capacitance.

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 $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$. Our MTJs are practically identical in design and differ only in that the former have perpendicular anisotropy of magnetic electrodes, and the latter use magnetic electrodes with uniaxial anisotropy in the plane. Magnetic contacts were fabricated by magnetron sputtering of alloy magnetic targets $Tb_{22}Co_5Fe_{73}$, $Tb_{19}Co_5Fe_{76}$, $Co_{80}Fe_{20}$, $Co_{30}Fe_{70}$ and as well dielectric targets of praseodymium oxide Pr_6O_{11}. MTJ were fabricated by photolithography on a substrate of fused quartz $S=14x14$ mm in the structure $Au/Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_{76}/Au$ and $Au/Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}/Au$. We investigated tunnel contacts with two different thicknesses of Pr_6O_{11} ($d_1=1\text{-}1.2$ *nm* or $d_2=1.5\text{-}1.8$ *nm*). The distance between individual tunnel contacts was at least *5 mm*. The amorphous ferrimagnetic films of TbCoFe have a large perpendicular magnetic anisotropy energy and the value of their coercive force depends on the concentration of components in the film. At $T=300$ K, the coercive force of the $Tb_{22}Co_5Fe_{73}$ film is $H_1 \approx 3x10^5$ *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. Such a field 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 $H_1 \approx 2.5x10^3$ *A/m* and the $Co_{80}Fe_{.20}$ film $H_2 \approx 6x10^3$ *A/m*.

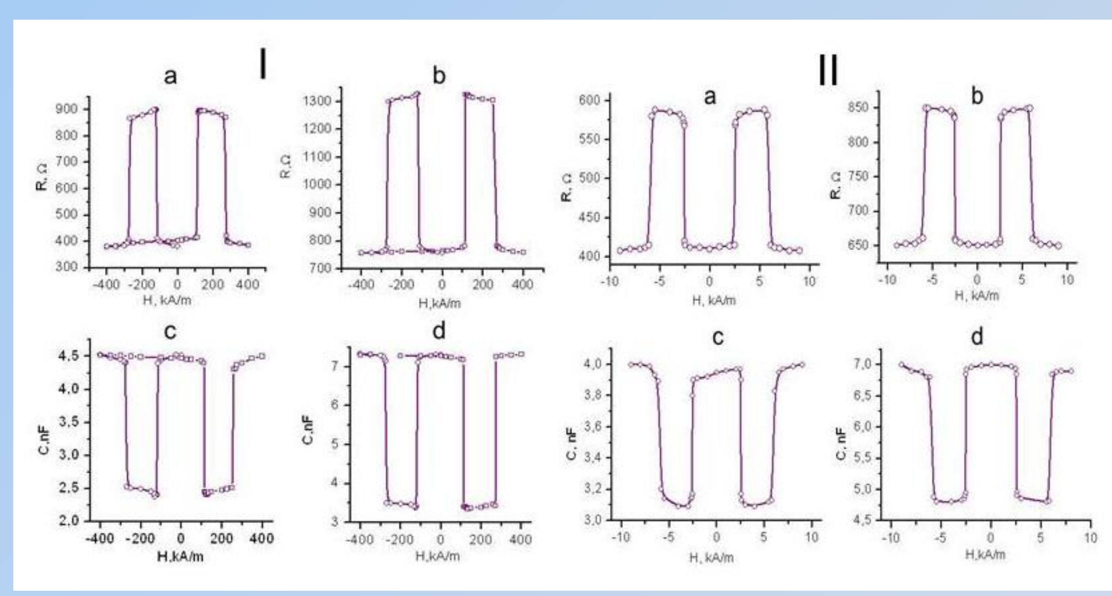

Fig. 2. (I) - change in capacitance and resistance of MTJ with perpendicular anisotropy of electrodes $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ depending magnitude of permanent magnetic field: **a** and **c** – the thicknes of Pr_6O_{11} nanolayer is $d_1=1\text{-}1,2$ *nm*; **b** and **d** – the thicknes of describes the process when the thicknes of Pr_6O_{11} nanolayer is $d_1=1,5\text{-}1,8$ *nm*. (II) - change in capacitance and resistance of MTJ $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$, in which magnetic electrodes have uniaxial anisotropy in plane:**a** and **c** – thicknes of Pr_6O_{11} nanolayer is $d_1=1\text{-}1,2$ *nm*; **b** and **d** – the thicknes of Pr_6O_{11} nanolayer is $d_1=1,5\text{-}1,8$ *nm*.

The value of TMR in the MTJ $Tb_{22}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19}Co_5Fe_{76}$ with perpendicular anisotropy of magnetic electrodes reached the value of TMR=120% at the thickness of the Pr_6O_{11} nanolayer $d_1=1\text{-}1.2$ *nm* and TMR=75% at the thickness of the Pr_6O_{11} nanolayer $d_1=1.5\text{-}1.8$ *nm*. The value of TMC in such MTJs reached the value of TMC=80% at the thickness of the Pr_6O_{11} nanolayer $d_1=1\text{-}1.2$ *nm* and TMC=110% at the thickness of the Pr_6O_{11} nanolayer $d_1=1.5\text{-}1.8$ *nm* . The MTJ $Co_{80}Fe_{20}/Pr_6O_{11}/Co_{30}Fe_{70}$, in which electrodes have uniaxial anisotropy in plane, has smaller absolute value of TMR and TMC. The value of TMR in such MTJs reached the values TMR=40% when the thickness of the Pr_6O_{11} nanolayer $d_1=1\text{-}1.2$ *nm* and TMR=30% when thickness of the Pr_6O_{11} nanolayer $d_1=1.5\text{-}1.8$ *nm*. The value of TMC in such MTJs reached the values TMC=25% when the thickness of the Pr_6O_{11} nanolayer $d_1=1\text{-}1.2$ *nm* and TMC=45% when the thickness of the Pr_6O_{11} nanolayer $d_1=1.5\text{-}1.8$ *nm* .

As we noted above, the most promising direction for the practical use of the TMR and TMC effects in the MTJ is the construction of media for recording and reading information based on them. In this work, we present a scheme and a method for recording and reading information from an information carrier based on MTJs. A feature of such a spin information carrier is that it uses double MTJs as a memory cell.

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