Magnetocapacitance Effect in Tunnel Contact with Perpendicular Anisotropy of Magnetic Electrodes

Krupa M.M.

Institute of magnetism NAN and MEN of Ukraine, 03142, Kiev, bulv.Vernadskogo, 36-b, Ukraine

INTRODUCTION

The great interest in magnetic tunnel junctions (MTJ) is caused by the fact that a large value of tunnel magnetoresistance (TMR) was obtained in them, and a significant change in capacitance in the magnetic field which is associated with the appearance of spin capacity [1-3] at the magnetic metal/dielectric interface was registered. This effect is called tunnel magnetocapacitance (TMC) effect, and it is considered one of the most promising effects that can have practical applications in memory elements and other spintronic devices. Large values of TMR and TMC in such MTJ are associated with the features of the electronic structure of the Fe/MgO interfaces where the effective spin-dependent tunneling effect is ensured by a good agreement between the crystal lattice parameters of Fe electrode and of MgO barrier nanolayer.

In this report are presented the results of experimental studies of TMR and TMC in magnetic tunnel contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$, in which the magnetic electrodes have perpendicular anisotropy and are magnetized perpendicular to the plane of the tunnel contact, and the barrier layer Pr_6O_{11} is high energy-gap semiconductor and paramagnet with low Curie temperature. It is shown, that in such MTJ, with their antiparallel magnetization, a strong magnetic field gradient in the barrier layer near each electrode is created. The big gradient of a magnetic field arises only in in the direction of the magnetisation of magnetic electrodes. In the barrier layer arises an almost uniform magnetic field. This field is directed perpendicular to the direction of magnetization of the magnetic electrodes. Such strong changes in the distribution of the magnetic field lead to the appearance of an additional spin capacity near each magnetic electrode and an additional energy barrier for electrons with a major polarization, which makes it possible to obtain large values of TMR and TMC in MTJ with perpendicular magnetization of the electrodes.

EXPERIMENTAL and RESULTS

.Ferrimagnetic films were produced by magnetron sputtering of $Tb_{22}Co_5Fe_{73}$ and $Tb_{19}Co_5Fe_{76}$ alloy targets. The contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ were formed by photolithography in the film multilayer structure: Au ($d\approx 15nm$), $Tb_{22}Co_5Fe_{73}$ ($d \approx 30$ nm), Pr_6O_{11} ($d_1 \approx 1$ nm or $d_2 \approx 1,5$ nm) and $Tb_{19-\delta}Co_5Fe_{76}$ ($d \approx 30$ nm). The high energy of the perpendicular anisotropy and large coercive force ensures a long-term storage of saturation magnetization in these films. The large difference in the magnitude of coercive force allowed us to remagnetize $Tb_{19-\delta}Co_5Fe_{76}$ film without changing the direction of magnetization of the $Tb_{22-\delta}Co_5Fe_{731}$ film The contact area of the each tunnel contact was $S=60\text{-}65\ \mu m^2$. The characteristics of the $Tb_{22-\delta}Co_5Fe_{731}$ and $Tb_{19-\delta}Co_5Fe_{76}$ films described above show that they are a good model medium for studying the effects of TMR and TMC in tunneling magnetic contacts with magnetic films that have perpendicular anisotropy.

In our research, we used two groups of tunnel contacts, which were selected based on the results of resistance measurements. The four-probe method was used to measure magnetoresistance in our tunnel contacts, and the measuring ac bridge was used to measure magnetocapacitance. The electrical voltage and current signals from the tunnel contacts and the compensation signal from the capacitance measurement bridge were converted into digital form recorded by a computer and processed with the help of a special program. Permanent magnetic field was created by using an electromagnet, which was also controlled by the computer. The measuring device described above allows us to measure resistance from 10 microohm in the frequency range of *0-30 kHz* and capacitance from *10* picofarad in the frequency range of *0-300 Hz*.

Scientific interest in MTJ with perpendicular anisotropy is based on the fact that a very high magnetic field gradient is created in such tunnel contacts. The scattering magnetic field for two glued magnets, in which the magnetic moments are directed toward each other, can be described by the following expression [4] $H_p \approx 4M_s \ln(a/r)$. Here M_s is value of the magnetic moment of magnets, a is distance between magnets r is the distance from the middle line of gluing to the measurement point.

The measurement results of the magnetoresistance and the magnetocapacitance of of our contacts for an alternating current with frequency of *140 Hz* are presented in Figure 2. The resistance of tunnel contacts with a smaller thickness of the barrier nanolayer Pr_6O_{11} $d_1 \approx 1$ nm changes more strongly during remagnetization than in tunnel contacts with the thickness of the barrier nanolayer $d_2 \approx 1.5$ nm. It can be seen from that the value of TMR reaches *110%* for contacts of the first type, about *70%* for contacts of the second type. Here $TMR = R_{max} - R_{min}/R_{min}$, R_{max} and R_{min} are the maximum and minimum resistances of contacs under investigation.

The capacity of tunnel contacts with a smaller thickness of the barrier nanolayer Pr_6O_{11} $d_1 \approx 1$ nm changes during remagnetization less than that of contacts with a larger thickness of the barrier nanolayeranolayer $d_1 \approx 1,5$ nm. The value of tunnel magnetocapacitance was determined as $TMC=(CP - CAP)/CAP$, where CP and CAP is the capacitance in the parallel and anti-parallel magnetization states for both magnetic films. The value (Fig. 1) of TMC in the best MTJ samples reached values of TMC$\approx$*100%* for MTJ contacts of the second type (Pr_6O_{11} $d_1 \approx 1,5$ nm) and TMC $\approx$ *80%* for MTJ contacts of the first type (Pr_6O_{11} $d_1 \approx 1$ nm). Such sufficiently high values of tunnel magnetoresistance and tunnel magnetic capacitance are caused by spin-dependent scattering and spin capacitance that occurs at interfaces of $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}$ and $Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$.

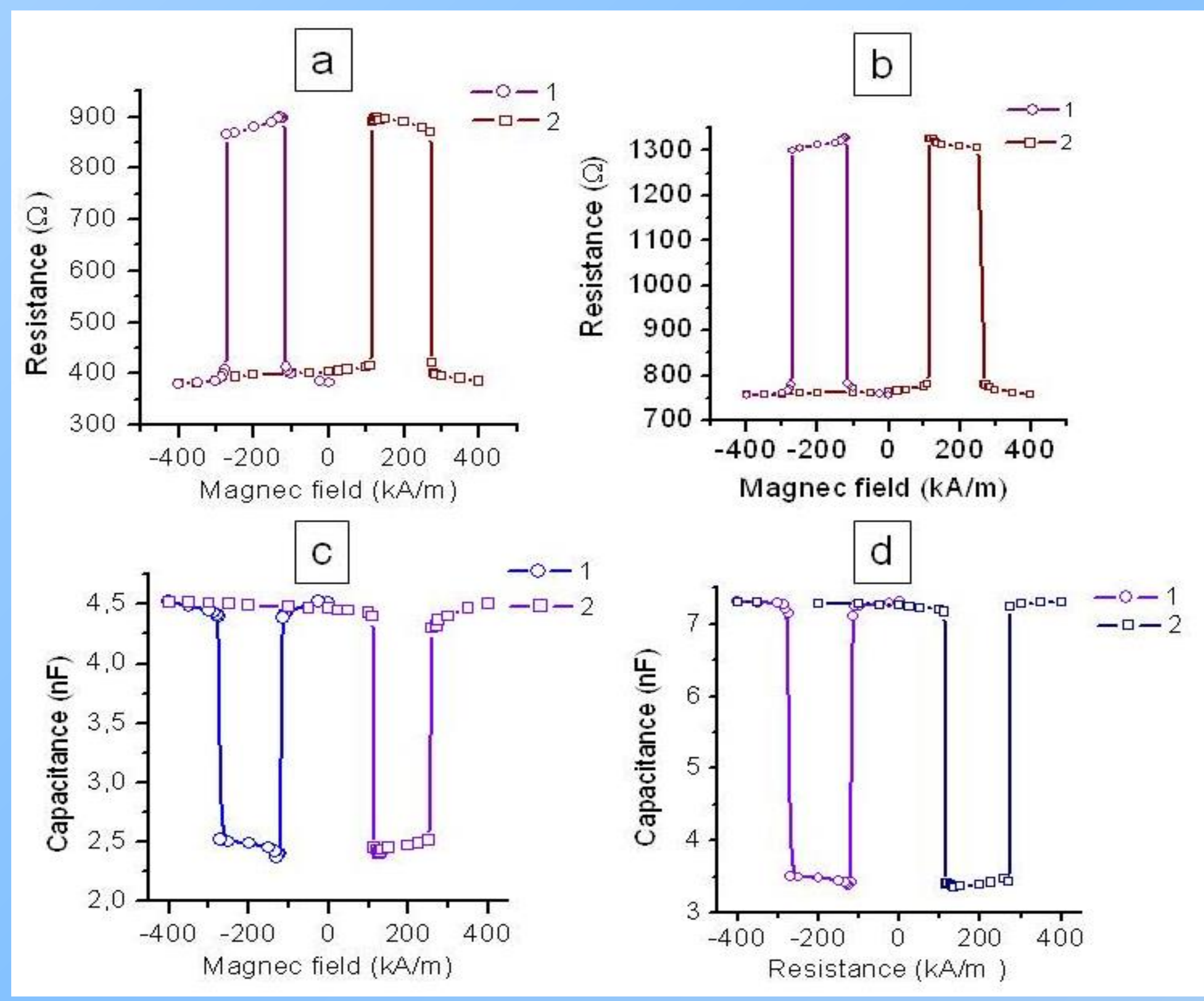

Fig. 1. Change in resistance and capacitance of parallel magnetized tunnel contacts $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ with different thickness d of the barrier layer depending on the direction and magnitude of the permanent magnetic field: (a) and (c) - curves for contact with $d_1 \approx 1$ nm, (b) and (c) – curves for contact with $d_1 \approx 1,5$ nm: curve 1 describes the process when the field H changes from *0* to *–400 kA/m*, curve 2 describes the process when the the field H changes from *–400 kA/m* to *+400 kA/m*.

On both interfaces the value of the spin-dependent energy barrier and the value of the spin-dependent scattering strongly changes at transition from parallel to antiparallel magnetisation of magnetic electrodes in our MTJ. With the parallel orientation of the magnetization of the electrodes, there is an almost uniform magnetic field in the barrier layer. In such a uniform field, the penetration depth of electrons from the magnetic electrode into the barrier nanolayer does not depend on their spin polarization, but is determined only by the difference in chemical potentials. With antiparallel magnetization of the electrodes, a strong magnetic field gradient near each electrode is created. Such a strong gradient of the magnetic field occurs along the magnetization of the magnetic electrodes $|dH/dx|>>|dH/dy|$ and $|dH/dx|>>|dH/dz|$ and its value can be estimated as $dH_i/dx|\approx H_i/2d$, where H_i ($i=1,2$) is the magnetic field strength on the surface of each magnetic electrode, d is the thickness of the barrier layer. In the barrier layer, when the electrodes are magnetized antiparallel , an almost uniform magnetic field arises, which is directed perpendicularly to the direction of magnetization of the electrodes. The magnitude of the components of this field can be estimated as $H_y = H_z \approx (H_1^2 + H_2^2)^{1/2}$

A high-gradient magnetic field causes a change in the depth of penetration of major and minor electrons in the interface region of the barrier nanolayer, and also causes a redistribution of conduction electrons of the barrier layer. Such a non-uniform distribution of conduction electrons causes a non-uniform distribution of holes in depth in the semiconductor barrier nanolayer. As a result, an energy barrier for electrons with major spin polarization is formed near each magnetic electrode and an additional capacitance appears. This additional capacity is called spin capacity. This leads to the increase in resistance and decrease in the capacity of our magnetic contacts at antiparallel magnetization of their electrodes. Since our Pr_6O_{11} barrier layer is paramagnetic, the change in the magnetic field described above can lead to significant changes in the magnetization of this barrier layer when the electrodes are antiparallel magnetized. The greatest changes of the magnetic field will be observed in $Tb_{22-\delta}Co_5Fe_{73}/Pr_6O_{11}$ and $Pr_6O_{11}/Tb_{19-\delta}Co_5Fe_{76}$ interfaces, and such changes in the magnetization of the barrier layer can significantly enhance the TMR and TMC effects in our tunnel magnetic contacts.

The given results show the prospects of practical use of MTP with electrodes having perpendicular anisotropy. Of course, for the practical use of such MTP, a material with high spin polarization and low coercive force for the magnetic electrodes must be used.

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