Research Article

Tunnel Magnetoresistance of $\text{Fe}_3\text{O}_4/\text{MgO}/\text{Fe}$ Nanostructures

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A magnetic tunnel junction $\text{Fe}_3\text{O}_4/\text{MgO}/\text{Fe}$ with (001) layer orientation is considered. The junction magnetic energy is analyzed as a function of the angle between the layer magnetization vectors under various magnetic fields. The tunnel magnetoresistance is calculated as a function of the external magnetic field. In contrast with junctions with unidirectional anisotropy, a substantially lower magnetic field is required for the junction switching.

Tunnel magnetic junction is one of the most important objects in spintronics. The interest in such structures is related to the tunnel magnetoresistance (TMR) effect used to create magnetic random access memory (MRAM).

Investigations of magnetic tunnel structures are directed to searching new effects, as well as studying material combinations, which are capable to ensure better characteristics.

$\text{Fe}_3\text{O}_4/\text{MgO}/\text{Fe}$ tunnel junctions seem promising in several extents. Besides technological advantages, such structures have interesting physical properties. First, Fe_3O_4 is so-called half metal in which only the carriers with one spin orientation take part in electric transport that leads to increasing TMR [1]. With this fact as well as higher resistivity compared to metals, higher spin resistance [2] is related to Fe_3O_4 layer, which may act as an ideal spin injector. Second, because of cubic crystallographic symmetry, Fe and Fe_3O_4 have more than one magnetic anisotropy axes. This increases the number of stationary configurations of the magnetic junction and, correspondingly, the number of possible variants of switching between those configurations. The latter feature is the subject of consideration in present work.

Let us consider a tunnel $\text{Fe}_3\text{O}_4/\text{MgO}/\text{Fe}$ junction with (001) layer orientation. As mentioned, Fe and Fe_3O_4 , both, have the same cubic symmetry but with different sign of the magnetic anisotropy energy: positive in Fe and negative (at room temperature) in Fe_3O_4 [3]. Therefore, there are three easy axes directed along the cube edges [100], [010],

[001] in Fe single crystal, while four easy axes along the cube diagonals [111], $[\bar{1}\bar{1}1]$, $[1\bar{1}\bar{1}]$, $[\bar{1}1\bar{1}]$ in Fe_3O_4 single crystal. In a thin layer with (001) orientation, the easy axes lie in the layer plane because of high shape anisotropy (this is valid when the magnetic anisotropy energy density is low compared to the demagnetization field energy density $2\pi M^2$, M being the saturation magnetization). In such a case, the easy axes in Fe(001) layer will be [100] and [010], while those in Fe_3O_4 (001) layer will be [110] and $[\bar{1}\bar{1}0]$, whereas [100] and [010] axes will be hard ones.

The anisotropy energy density in Fe is higher by several times (in magnitude) than that in Fe_3O_4 (in single crystals at room temperature, $4.7 \times 10^4 \text{ J/m}^3$ and $-1.2 \times 10^4 \text{ J/m}^3$, resp., [3]). Therefore, Fe_3O_4 layer will be switched earlier than Fe one under external magnetic field, other things being equal.

The presence of the MgO barrier layer avoids exchange coupling between Fe and Fe_3O_4 layers. As to the dipole magnetic interaction between the layers, such a coupling is a weak edge effect when the layer thickness is small compared to the layer lateral sizes. So we assume the responses of the Fe and Fe_3O_4 layers to magnetic field to be mutually independent.

Let us consider behavior of the Fe_3O_4 (001) layer with [100] (hard) axis parallel to the Fe layer [100] (easy) axis. The external magnetic field is assumed to be directed along the same axis. Let us track how the Fe_3O_4 layer magnetization direction changes under varying the applied magnetic field H .

FIGURE 1: The dependence of the (dimensionless) magnetic energy of the Fe_3O_4 layer on the magnetization vector orientation under various magnetic fields.

The magnetic energy density takes the form

$$U(\theta) = -MH \cos \theta - |K| \cos^2 \theta \sin^2 \theta, \quad (1)$$

where K is the (negative) anisotropy energy density, θ is the angle between the layer magnetization vector and $[100]$ axis.

The equilibrium condition is the equality

$$\frac{dU}{d\theta} = 0, \quad (2)$$

the equilibrium stability condition is the inequality

$$\frac{d^2U}{d\theta^2} > 0. \quad (3)$$

The condition (2) with (1) taken into account is reduced to a trigonometric equation

$$(2\cos^3 \theta - \cos \theta - h) \sin \theta = 0, \quad (4)$$

where

$$h = \frac{MH}{2|K|} = \frac{H}{H_a}, \quad (5)$$

is the dimensionless magnetic field, $H_a = 2|K|/M$ is the anisotropy field.

In the angle interval from 0 to π , (4) has the following solutions stable in different ranges of h values:

$$\theta_1 = 0, \quad (6)$$

stability at $h > 1$;

$$\theta_2 = \pi, \quad (7)$$

stability at $h < -1$;

$$\theta_3 = \arccos\left(\sqrt{\frac{2}{3}} \cos\left(\frac{1}{3} \arccos \frac{h}{h_0}\right)\right) \quad (8)$$

$$\theta_4 = \arccos\left(-\sqrt{\frac{2}{3}} \cos\left(\frac{\pi}{3} - \frac{1}{3} \arccos \frac{h}{h_0}\right)\right),$$

where $h_0 = \sqrt{2/27} \approx 0.272$, stability at $|h| < h_0$;

$$\theta_5 = \arccos\left(-\sqrt{\frac{2}{3}} \cos\left(\frac{\pi}{3} + \frac{1}{3} \arccos \frac{h}{h_0}\right)\right), \quad (9)$$

instability;

$$\theta_6 = \arccos\left(\sqrt{\frac{2}{3}} \cosh\left(\frac{1}{3} \operatorname{arccosh} \frac{h}{h_0}\right)\right), \quad (10)$$

stability at $h_0 < h < 1$;

$$\theta_7 = \arccos\left(-\sqrt{\frac{2}{3}} \cosh\left(\frac{1}{3} \operatorname{arccosh} \left(-\frac{h}{h_0}\right)\right)\right), \quad (11)$$

stability at $-1 < h < h_0$.

It is seen that two solutions, θ_3 and θ_4 , are stable in the $-h_0 < h < h_0$ range. Realization of either depends on the prehistory. With decreasing the magnetic field from $h = +\infty$ to certain value $h < -1$ at which the Fe layer magnetization does not reverse, the following sequence of states takes place:

$$\theta_1 \xrightarrow{1} \theta_6 \xrightarrow{h_0} \theta_3 \xrightarrow{-h_0} \theta_7 \xrightarrow{-1} \theta_2; \quad (12)$$

the indices over the arrows show the magnetic field values at which corresponding switching occurs. With changing the field in the opposite direction another sequence takes place:

$$\theta_2 \xrightarrow{-1} \theta_7 \xrightarrow{-h_0} \theta_4 \xrightarrow{h_0} \theta_6 \xrightarrow{1} \theta_1. \quad (13)$$

These sequences may be tracked also in Figure 1 where the (dimensionless) magnetic energy is shown as a function of θ angle with various h values.

In Figure 2, χ angle between the layer magnetization vectors is shown as a function of the magnetic field before (solid lines and arrows) and after (dashed lines and dotted arrows) switching the Fe layer which has higher anisotropy energy, so that higher magnetic field is required for its switching. This layer, magnetized along the positive direction of $[100]$ axis initially, is switched to the opposite direction by some magnetic field $h = h_1 < -1$ having negative direction. The sequence (13) is not realized in this case.

The change of the junction magnetic configuration manifests itself as change of the junction resistance. The

FIGURE 2: The field dependence of the χ angle between the Fe and Fe_3O_4 layer magnetization vectors before (solid lines and arrows) and after (dashed lines and dotted arrows) switching the Fe layer which has higher anisotropy energy.

conductance of a magnetic tunnel junction with χ angle between the layer magnetization vectors takes the form [4]

$$G(\chi) = G_P \cos^2 \frac{\chi}{2} + G_{AP} \sin^2 \frac{\chi}{2}, \quad (14)$$

where G_P , G_{AP} are the junction conductances under parallel ($\chi = 0$) and antiparallel ($\chi = \pi$) relative orientation of the layers, respectively.

It is convenient to take the following ratio as a measure of the junction resistance change:

$$F(h) \equiv \frac{R(h) - R_P}{R_P} = \frac{\rho(1 - \cos \chi(h))}{2 + \rho(1 + \cos \chi(h))}, \quad (15)$$

where $R(h) = 1/G(\chi(h))$, $\rho = (R_{AP} - R_P)/R_P$ is TMR defined in a usual way [1]. The latter is related with the layer spin polarizations P_1 , P_2 [1]:

$$\rho = \frac{2P_1 P_2}{1 - P_1 P_2}. \quad (16)$$

With $P_1 = 0.44$ (Fe [5]), $P_2 = 1$ (Fe_3O_4) we have $\rho \approx 1.6$.

To obtain the junction resistance change as a function of the magnetic field $F(h)$, the $\chi(h)$ dependence should be substitute to (15). With the minimum magnetic energy analysis made above taking into account, we obtain the results shown in Figure 3. As in Figure 2, the solid and dashed lines show the resistance change before and after the Fe layer switching, respectively. A possibility of the switching between stationary states (marked with black squares) is seen with different resistances.

In comparison with the standard TMR, where the magnetic field equal to the anisotropy field of the layer is required for switching, the substantially lower field $h = h_0$ is needed in the considered case.

FIGURE 3: The junction resistance change as a function of the magnetic field. The black squares mark the stationary states with different resistances between which the switching occurs.

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