Surface roughness of layers and giant magnetoresistance of magnetic multilayer structures

A. I. Morozov and A. S. Sigov

Moscow State Institute of Radio Engineering, Electronics, and Automation (Technical University), 117454 Moscow, Russia[1)]

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A model which explains the giant magnetoresistance of magnetic multilayer structures in terms of a breakup of the magnetic layers into domains is proposed. Since the exchange interaction between layers is an oscillatory function of the thickness of the nonmagnetic layer, fluctuations in thickness give rise to regions with an interaction of the opposite sign. This effect leads to a breakup of the layers into domains. Conditions for this breakup are discussed. This model can explain the entire set of experimental data. © *1995 American Institute of Physics.*

Since the discovery of the giant magnetoresistance in magnetic multilayer structures,[1] this effect has been the subject of many experimental and theoretical studies (see, for example, a review[2]). A magnetic multilayer structure consists of alternating layers of a ferromagnetic metal (Fe, Co) and a nonmagnetic metal (Cr, Cu, Ru). If there is no external magnetic field parallel to the magnetization of the ferromagnetic layers, which lies in the plane of the layer at small thicknesses, the resultant magnetic moment of the structure is zero. This circumstance is usually interpreted as an antiferromagnetic interaction of the layers. The application of a magnetic field H gives rise to a resultant magnetization; as H is increased, this magnetization reaches saturation. The process is accompanied by a decrease in the resistance of the structure for a current flowing along the layers. The decrease amounts to several tens of percent. This effect has been called a "giant magnetoresistance." Figure 1 shows the typical behavior of the quantity $G(H)=[\tilde{R}(H)-\tilde{R}_{sat}]/\tilde{R}_{sat}$ as a function of H; here $\tilde{R}_{sat}$ is the resistance in a magnetic field $H>H_{sat}$. In the interpretation of this effect it is usually assumed that the magnetization is uniform along the layer and that the angle between the magnetization vectors of the layers changes in an external field. According to the existing theories, the magnetoresistance stems from a dependence of the mean free paths of electrons with different spin directions on the relative orientation of the magnetizations of the layers. That interpretation, however, runs into the following difficulties:

(1) The exchange interaction between the ferromagnetic layers is an RKKY interaction, and oscillates along the thickness of the interlayer,[3–10] changing sign. Experimentally, on the other hand, an antiferromagnetic state is observed at any thickness of the interlayer in a zero magnetic field.[11,12]

(2) Experiments show that the quantities $G(0)$ and H_{sat} oscillate as a function of the thickness of the nonmagnetic interlayer. [11–18] None of the mechanisms for the magne-

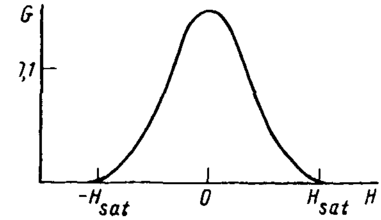

FIG. 1. Resistance of the multilayer structure versus the longitudinal external magnetic field.

toresistance which have been proposed[19–24] predicts an oscillatory behavior of this sort for the quantity G.

All these contradictions can be resolved by assuming that the magnetic layers break up into regions (domains) with parallel and antiparallel directions of the magnetizations of the layers. In this case, the magnetoresistance is determined primarily by a scattering of electrons by the boundaries of these regions. To analyze the reasons for such a breakup, we consider the example of a three-layer system consisting of two magnetic layers separated by a nonmagnetic interlayer of thickness d.

Since the demagnetization factor of a layer is zero when the magnetization is parallel to the layer, the breakup into domains is caused by fluctuations of the exchange interaction between layers. These fluctuations are caused by random changes in the thickness of the interlayer, i.e., by the roughness of the interfaces between layers. This roughness is caused by the presence of steps at the interfaces, which lead to changes of monolayer in the thickness of the layer. An elementary estimate shows that the molecular field exerted by the atoms of the magnetic layer on the spin of an atom belonging to the first magnetic layer is dominated by the region directly opposite the atom, with a size on the order of the thickness of nonmagnetic interlayer, d.

According to Ref. 3, the exchange integral for the case of an interaction between layers is

$$J_{\perp}(d)=J_0\frac{\sin(2k_Fd)}{(2k_Fd)^2}\equiv\tilde{J}_{\perp}\sin(2k_Fd), \tag{1}$$

where $J_0=\text{const}$, and k_F, is the Fermi wave vector of the electrons. Since the thickness of the interlayer is comparable to the period of the oscillations of the exchange interaction between layers, $\lambda=\pi/k_F$, an increase or decrease in the thickness of the interlayer by one monolayer can lead to a change in the sign of the exchange interaction of spins belonging to the different magnetic layers.

We start from the assumption that the typical size of the steps at the surface of a layer, R, is much greater than d. In the opposite case, a breakup into domains does not occur, as it shown below. In the case $R\gg d$, it can be assumed that the exchange interaction between layers is a function of the local thickness of the nonmagnetic interlayer. We first consider an isolated atomic step of infinite length. We assume that the z axis of our coordinate system is perpendicular to the layers, that the edge of the step coincides with the y axis, and that the x axis lies in the plane of the layer and is perpendicular to the step. The exchange integral of the interaction between layers is then

$$J_\perp(x)=\begin{cases} J_1, & x<0, \\ J_2, & x>0. \end{cases} \tag{2}$$

We assume $J_1>0$ and $J_2<0$.

In this case a domain wall forms near the edge of the step. This wall separates a half-space with a parallel orientation of the spins of the magnetic layers, at $x<0$, from a half-space with an antiparallel orientation of the spins, at $x>0$.

Since the domain wall arises in our case because of an exchange interaction between layers, whose energy is much greater than the energy of the magnetic anisotropy, the thickness of these domain walls may be much smaller than in the case of ordinary domains walls in a ferromagnet. Let us calculate the surface energy and thickness of the domain wall in the exchange approximation. How the spins of the layers are oriented in the xy plane is unimportant in this approximation, as is the particular plane in which the spin rotates.

By analogy with Ref. 25, we write the increment in the energy of the exchange interaction of the spins in the layers due to the irregularity as follows:

$$W_1=\int\left[\frac{\alpha_1}{2}(\theta_1')^2+\frac{\alpha_2}{2}(\theta_2')^2\right]d^2\boldsymbol{\rho}, \tag{3}$$

where θ_1 and θ_2 are the angles through which the spin vectors rotate in the first and second layers, respectively, and the prime means differentiation with respect to x. In order of magnitude we have

$$\alpha_i\sim J_\parallel^i S_i^2 l_i/b_i, \quad i=1,2, \tag{4}$$

where $J^i_\parallel$ is the exchange integral between neighboring spins in a layer, l_i is the thickness of a magnetic layer, S_i is the expectation value of the atomic spin, and b is the interatomic distance. The energy of the interaction between layers is given in the mean-field approximation by

$$W_2=-\int\beta(x)\cos(\theta_1-\theta_2)d^2\boldsymbol{\rho}, \tag{5}$$

$$\beta(x)=\begin{cases} \beta_1, & x<0, \\ -\beta_2, & x>0, \end{cases}\sim J_\perp(x)S_1S_2b^{-2}. \tag{6}$$

Varying the sum W_1+W_2 with respect to θ_1 and θ_2, we find the system of equations

$$\alpha_1\theta_1''-\beta\sin(\theta_1-\theta_2)=0, \quad a_2\theta_2''+\beta\sin(\theta_1-\theta_2)=0, \tag{7}$$

with the boundary conditions $\theta_i'\to0$ at $x\to\pm\infty$, $\theta_i\to0$ at $x\to-\infty$, and $|\theta_1-\theta_2|\to\pi$ at $x\to+\infty$. A solution of this equation is $\theta_2=-\alpha_1\theta/(\alpha_1+\alpha_2)$; $\theta_1=\alpha_2\theta/(\alpha_1+\alpha_2)$, where $\alpha^*=\alpha_1\alpha_2/(\alpha_1+\alpha_2)$, and the dependence $\theta(x)$ is given by

$$\cos\frac{\theta}{2}=-\tanh\left[\left(\frac{\beta_1}{\alpha^*}\right)^{1/2}(x+x_1)\right], \quad x<0;$$

$$\sin\frac{\theta}{2}=\tanh\left[\left(\frac{\beta_2}{\alpha^*}\right)^{1/2}(x+x_2)\right],\quad x>0. \tag{8}$$

The constants x_1 and x_2 are found from the condition that the derivative $\theta'(x)$ is continuous at $x=0$. This condition leads to the equation

$$\tan\frac{\theta}{2}\bigg|_{x=0}=\left(\frac{\beta_2}{\beta_1}\right)^{1/2}. \tag{9}$$

It is easy to see that under the condition $\beta_1 \gg \beta_2$ essentially the entire wall is in the region $x>0$, while under the condition $\beta_1 \ll \beta_2$ it is at $x<0$. In the case $\alpha_1=\alpha_2$ the spins of the layers rotate 90° in different directions. A 90° domain structure of specifically this type has been observed[26] in a Fe/Cr superlattice. If one of the values of α is much greater than the other, on the other hand, i.e., if the thickness of one of the layers is considerably greater, then essentially the entire spin rotation occurs in the thinner layer, and the spins in the thick layer turn through a small angle.

The typical width of the domain wall, δ, is

$$\delta=\pi\left(\frac{\alpha^*}{\min(\beta_1,\beta_2)}\right)^{1/2}\sim\pi b\left(\frac{J_{\parallel}l_{\min}}{\tilde{J}_{\perp}b}\right)^{1/2}\sim\pi d\left(\frac{J_{\parallel}l_{\min}}{J_0 b}\right)^{1/2}\gg d, \tag{10}$$

where $l_{\min}$ is the smaller of the thickness of the two magnetic layers. For the values $l/b\sim 3$–5, $J_{\parallel}/J_0\sim 1-10$, and $d\sim 10$ Å we find $\delta\sim 100$ Å. This result is much smaller than the width of a domain wall in iron (800 Å).

Substituting solution (8) into the functional W_1+W_2, we find the energy of the domain wall integrated over the thickness of the layers, i.e., the energy per unit length of a domain line at the surface of two layers, as the difference between this energy and the sum of the energies of uniform states with $\theta=0$ at $x<0$ and $\theta=\pi$ at $x>0$:

$$\sigma=4(\alpha^*)^{1/2}[\beta_1^{1/2}+\beta_2^{1/2}-(\beta_1+\beta_2)^{1/2}]$$
$$\sim d^{-1}S^2[J_{\parallel}J_0 l_{\min}/b]^{1/2}\sim b^{-1}S^2[J_{\parallel}\tilde{J}_{\perp}l_{\min}/b]^{1/2}. \tag{11}$$

What conditions favor the breakup of the magnetic layers into domains? We assume that the typical size of the steps, R, is the same in the two directions. We assume that a domain with a typical size $L>R$ arises at the surface of a layer. When a domain forms, the energy increases by an amount on the order of σL. Since we have $L>R$, there are regions inside the domain with both $J_{\perp}>0$ and $J_{\perp}<0$. Regions of one type outweigh the regions of the other type in a random fashion by an amount on the order of $N^{1/2}$, where N is the number of such regions: $N=L^2/R^2$. As a result, the decrease in the layer-interaction energy is $S_1S_2|J_{\perp}|R^2b^{-2}N^{1/2}\sim|J_{\perp}|S_1S_2LR/b^2$. The change in the energy per spin is

$$\epsilon=-|J_{\perp}|S_1R_2R/L+\sigma b^2/L. \tag{12}$$

The maximum of this function for $\epsilon<0$ occurs at $L=R$, while for $\epsilon>0$ it occurs as $L\to\infty$. In the case

$$\sigma b^2\langle|J_{\perp}|S_1S_2R, \tag{13}$$

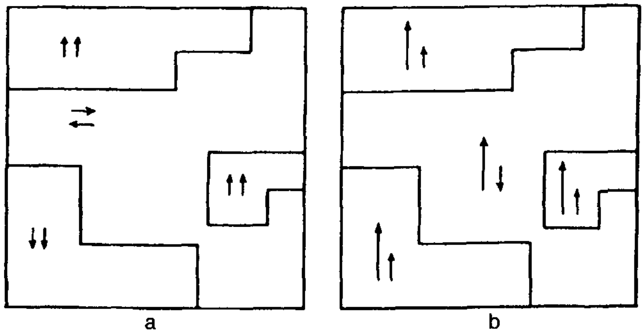

FIG. 2. Breakup of the layers into domains in the case of layers of identical thickness (a) and in the case $l_1 \gg l_2$ (b).

the magnetic layers thus break up into domains. Condition (13) is equivalent to the condition $R > \delta$.

How does this proposed picture of a breakup into domains make it possible to describe effects observed experimentally?

(1) A breakup into domains in the case of layers of identical thickness is accompanied by the disappearance of the resultant magnetic moment (Fig. 2a), in contrast with the case $l_1 \gg l_2$ (Fig. 2b).

(2) A magnetic field causes the layers to consist of a single domain, and it eliminates the contribution of the domain walls to the resistance.

(3) Since the thickness of the interlayer changes discretely, in steps of a monolayer thickness ζ, a change in the phase $\sin(2k_F d)$ in (1) by an amount $2k_F\zeta$ does not always lead to a change in the sign of the sine. If the thickness of the interlayer took on only two discrete values, and if the same sign of $J_\perp$ corresponded to these two values, then a breakup into domains would not occur, and there would be no magnetoresistance due to this mechanism. In actuality, there is a smoother distribution along the thickness of the interlayer, and the magnetoresistance does not vanish. Its magnitude is small, however, because of the low concentration of domain walls, with the values of the function $J_\perp(d)$ having the same sign for the thicknesses most commonly encountered (on the average over the area of the layer), d_1 and d_2. It reaches a maximum in the opposite case. As a result, oscillations arise in G as a function of the thickness of the nonmagnetic interlayer. By virtue of the discrete nature of the thickness of the interlayer, the period of these oscillations may be much greater than λ (Refs. 4–6).

(4) Since we have $J_\perp \propto d^{-2}$ and $\sigma \propto d^{-1}$, condition (13) breaks down at large thickness, and the magnetoresistance disappears. Because of the spread in the values of R, this effect occurs smoothly.

(5) A maximum of the coercive field H_{sat} is observed when the number of domains is at its maximum. Accordingly, the oscillations in H_{sat} are in phase with the oscillations of the magnetoresistance, in agreement with the experiments of Refs. 3–10.

(6) An increase in the roughness of the interfaces causes an increase in the width of

the distribution with respect to the thickness of the interlayer, and it also decreases the typical step size R. The first of these effects leads to a smoothing of the oscillations in G and H_{sat}; this effect occurs at large thickness of the interlayer. The decrease in R is initially accompanied by an increase in the number of domain walls and an increase in G, as was observed in Ref. 27. A further decrease in R, however, leads to a violation of inequality (13) and to a decrease in G. This conclusion agrees completely with the picture found in Ref. 28: The formation of a small number of steps at an interface led to an increase in G, but a further increase in the roughness reduced the value of the magnetoresistance.

[1)]e-mail: ber@glasnet.ru

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