3B2v7.51c GML4.3.1 MAGMA : 8771 Prod.Type:COM pp.1–3(col.fig.:NIL) ED:Chanakshi PAGN: bvr SCAN: BINDU

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Journal of Magnetism and Magnetic Materials ▮ (▮▮▮▮) ▮▮▮–▮▮▮

journal of magnetism and magnetic materials

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Interface roughness and unidirectional anisotropy of thin ferromagnetic film on uncompensated surface of antiferromagnet

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Abstract

Magnetization curves of a ferromagnetic film on antiferromagnetic substrate were investigated with account of the frustrations produced by interface roughness. The conditions of appearance of unidirectional anisotropy were obtained and its dependence upon roughness of film–substrate interface was found. © 2002 Published by Elsevier Science B.V.

Keywords: Anisotropy, unidirectional; Thin films, bilayer; Interface structure; Magnetization, curves

The unidirectional anisotropy reveals itself in the shift of magnetization curve of ferromagnetic film deposited on the surface of antiferromagnet. The phenomenon of unidirectional anisotropy has been considered in a number of papers (see e.g., the review [1]).

Let us consider the case when the spins of the antiferromagnet atomic plane parallel to the interface between ferromagnet and antiferromagnet are not compensated. In the framework of the simple model with ideally flat interface, the exchange interaction between spins of the film and spins of the substrate causes the film magnetization direction exceptioning. Remagnetization of the film in an external magnetic field gives rise to formation of domain wall in the antiferromagnetic substrate [2,3].

Energy consumption in wall generating leads to the shift of magnetization curve from the field-symmetrical position by the value [2,3]

$$B_E \sim \frac{(A_{af}K_{af})^{1/2}S_{af}^2}{Ma}, \qquad (1)$$

where B is magnetic induction, A_{af} is exchange stiffness of antiferromagnet, K_{af} is its anisotropy constant in the plane parallel to the film–substrate interface, M is magnetization of ferromagnetic film, and a is the film thickness.

A real interface is never ideally flat, but contains atomic steps changing the substrate local thickness by one atomic layer. On different side of the step the orientation of spins in upper atomic layer of antiferromagnet is opposite, therefore the steps on the interface give rise to spin frustrations regardless of the sign of exchange integral $J_{f,af}$ between the spins of the film and the substrate. The phase diagram of such a frustrated system has been investigated in the framework of the continuum model [4].

The origins of the unidirectional anisotropy for the case of compensated spins of antiferromagnet atomic plane parallel to the interface are discussed in Refs. [2,5].

The goal of the present paper is to study magnetization processes and to find the unidirectional anisotropy dependence on the roughness rate for the frustrated system: ferromagnetic film–antiferromagnetic substrate.

When finding the distributions of the order parameters in the film and in the substrate we suppose that both the magnetization vector, and the vector of antiferromagnetism lies in the plane parallel to the interface and are characterized by the angle $\theta_i (i = \mathrm{f}, \mathrm{af})$ between the order parameter vector and a certain given axis in the plane. Minimization of the exchange energy in the system film–substrate leads to the equations:

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0304-8853/01/$ - see front matter © 2002 Published by Elsevier Science B.V.
PII: S0304-8853(01)01361-0

$$\Delta\theta_i = 0 \tag{2}$$

with the following boundary conditions:(a)

$$\tilde{\Delta}\theta_{\mathrm{f}} - \frac{\partial\theta_{\mathrm{f}}}{\partial n} = 0, \tag{3}$$

at the free film surface, where $\tilde{\Delta}$ is two-dimensional Laplacian in the film plane, and $\partial/\partial n$ denotes the derivative in the direction of the outer normal to the interface plane;(b)

$$\tilde{\Delta}\theta_i - \frac{\partial\theta_i}{\partial n} = \pm\frac{J_{\mathrm{f,af}}S_{i+1}}{J_i S_i}\sin(\theta_i - \theta_{i+1}), \tag{4}$$

at the film–substrate interface, where J_i is the exchange integral, and S_i is the mean spin of the atom within the ith layer;(c)

$$\theta_{\mathrm{af}} = 0$$

in the substrate volume far from the interface. All distances are normalized to the lattice constant b, which is assumed to be the same in all layers.

The solution of the system of differential Eq. (2) with boundary conditions (3) and (4) giving the order parameter distributions in the structure considered has been found by numerical method for the case of periodic set of rectilinear atomic step edges parallel to each other. The x-axis of the coordinate system lies in the layer plane and is perpendicular to the step edges, and the z-axis is perpendicular to the layer plane (two-dimensional case). The functions $\theta_i(x,z)$ have been obtained by Fourier expansion with respect to x variable in the region $|x|<L$ with periodic boundary conditions.

Let us consider the remagnetization process in the range of parameters where the film retains its single-domain state.

The atomic steps divide the whole interface into regions of two types: in the regions of the first type the surface energy takes its minimum for parallel orientation of ferromagnetic and antiferromagnetic order parameters and in the regions of the second type the energy takes its minimum for antiparallel orientation.

If the characteristic distance R between atomic steps at the interface is less than some critical value

$$R_{\mathrm{c}} = \delta_{\mathrm{f}} \approx \gamma a, \tag{5}$$

where

$$\gamma = \frac{J_{\mathrm{f}}S_{\mathrm{f}}^2}{J_{\mathrm{af}}S_{\mathrm{af}}^2} \gg 1, \tag{6}$$

the film remains in a single domain state and static spin vortices arise near the interface in the substrate (Fig. 1).

Two lengths characterize the vortex. The width δ_0^{af} of the region around the step edge at the film–substrate interface where the value of $\theta_{\mathrm{f}} - \theta_{\mathrm{af}}$ differs from its optimum (0 for one side of the step and π for the other) minimizing the surface energy equals

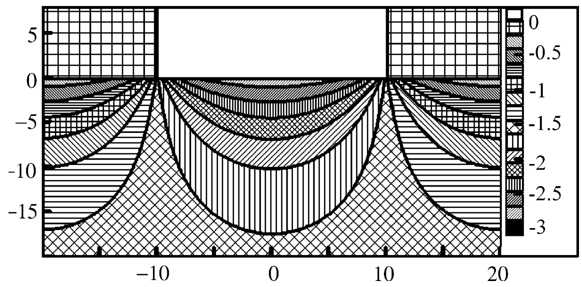

Fig. 1. Order parameter distributions in the vortex phase. The zero ordinate corresponds to the film–substrate interface. All distances are given in lattice constants. The ratio between hatching and the θ_i value in radians is shown in the inset.

$$\delta_0^{\mathrm{af}} \approx \frac{(J_{\mathrm{af}}S_{\mathrm{af}} + J_{\mathrm{f,af}}S_{\mathrm{f}})b}{J_{\mathrm{f,af}}S_{\mathrm{f}}} \sim b. \tag{7}$$

At all other part of the interface with the width $R \gg \delta_0^{\mathrm{af}}$, the angle $\theta_{\mathrm{f}} - \theta_{\mathrm{af}}$ equals to its optimum value. If the θ_{af} value at the interface is nonzero, then it changes continuously from this value to the zero one over the length R into the substrate volume.

If the mean film magnetization vector makes an angle ψ with the antiferromagnetic order parameter in the substrate volume, then the value of θ_{af} changes from ψ to zero in the vortex occupying the first type region, whereas in the vortices occupying the second type regions the value of θ_{af} changes from $\psi - \pi$ to zero.

By analogy with the "magnetic proximity" model [6], the surface energy density of the film–substrate system in an external magnetic field B_0 directed parallel to the film and at a φ angle to the axis can be written as

$$w = \frac{C}{2}\left[\frac{(\pi-\psi)^2}{2} + \frac{\psi^2}{2} - 2\eta\cos(\psi - \varphi)\right], \tag{8}$$

where

$$C \approx J_{\mathrm{af}}S_{\mathrm{af}}^2/Rb \tag{9}$$

and dimensionless parameter η equals

$$\eta = \frac{B_0 Ma}{C} \approx \frac{B_0 MaRb}{J_{\mathrm{af}}S_{\mathrm{af}}^2}. \tag{10}$$

Minimizing the energy (8), it is easy to find the equilibrium ψ value and the quantities $M_{\parallel} = M\cos(\psi - \varphi)$ and $M_{\perp} = M\sin(\psi - \varphi)$.

If the external magnetic field is parallel to the spontaneous magnetization of the film ($\varphi = \pi/2$), then for $\eta \geqslant -1$ the angle $\psi = \pi/2$ and $M_{\parallel} = M$. For $\eta < -1, |\eta| - 1 \ll 1$, the square root anomaly takes place:

$$\frac{\pi}{2} - \psi = [6(|\eta| - 1)]^{1/2}.$$

The quantity $M_{\parallel}$ has zero value at $\eta = -\pi/2$, so the

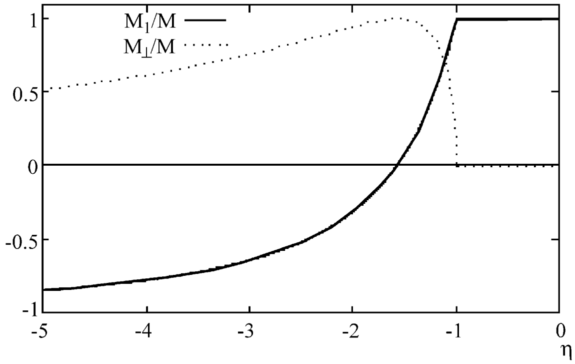

Fig. 2. Magnetization curve of the single domain film. Magnetic field is directed parallel to the spontaneous magnetization of the film.

magnetization curve is shifted to negative field region (Fig. 2). The unidirectional anisotropy field equals the value

$$B_E = \frac{\pi C}{2Ma} \propto R^{-1}. \tag{11}$$

For $|\eta| \gg 1, \eta < 0$, the $M_{\parallel}$ magnitude approaches its saturation value—M according to the $|B_0|^{-1}$ law. At the saturation, in the regions of the first and the second types the antiferromagnetic order parameter rotates by the angle $3\pi/2$ and $\pi/2$, respectively. Such a state is metastable. The difference between the energies of the metastable and the stable states at saturation exceeds the domain wall energy. So the domain wall in the antiferromagnet can arise, that results in the antiferromagnetism vector rotation near the interface by π and in diminishing the vortex energy.

Thus, one can deduce that the unidirectional anisotropy of single domain ferromagnetic film on uncompensated surface of antiferromagnet is caused by appearance of static spin vortices at a rough film–substrate interface, its value being inversely proportional to the mean distance between the atomic steps at the interface.

This work is partly supported by Russian Foundation for Basic Research, grant 00-02-17162.

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