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Internal structure of a domain wall in ultrathin magnetic film

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Abstract

Micromagnetic analysis of a domain wall internal structure in ultrathin magnetic film is carried out. The case when the film thickness is much smaller than the exchange length (the effective width of a Bloch line) is considered. It is shown that in this limiting case the angle of the domain wall twisting is very small and the domain wall has the quasi-Bloch structure.
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The internal domain wall (DW) structure in thin magnetic films was studied in detail [1, 2] in the approximation that the film thickness t is much greater than the exchange length $l_{ex} = (A/2\pi M_s^2)^{1/2}$ (A is the inhomogeneous exchange interaction constant, $4\pi M_s$ is the saturation magnetization). The exchange length represents the characteristic value of the effective width $\Lambda = (A/2\pi M_s^2)^{1/2}$ of the elements of DW internal structure which are called Bloch lines [1, 2]. Films of substituted yttrium–iron garnet that were an object of intensive investigation for last 20 years, were thick enough to provide the fulfillment of the condition $t \gg l_{ex} = \Lambda$ along with another one $t \gg \Delta_B$, where $\Delta_B = (A/K)^{1/2}$ is the effective width of the Bloch DW, K is the uniaxial anisotropy constant. Introduction of vertical and horizontal Bloch lines (the elements of the DW internal structure) played a key role in theoretical explanation of peculiarities of the DW dynamics in thin films of substituted yttrium–iron garnet [1, 2].

A different situation, namely, $t \ll l_{ex}$ is realized in ultrathin magnetic films that attracted a great deal of attention recently [3, 4], in connection with the giant magnetoresistance phenomenon observed in magnetic multilayers. There exist several experimental studies of domain structure and DW dynamics in ultrathin films [5–8]. All theoretical considerations [3, 4] were devoted to the analysis of stability of domain structure; but the DW internal structure has not been studied so far.

This presentation is a brief report of micromagnetic consideration of a DW structure in ultrathin magnetic film with $t \ll l_{ex}$.

The following geometry of the problem is considered. The axis of uniaxial anisotropy (the $0z$ axis) is normal to the film surface. The DW plane is the $x0z$ plane. The total energy density is the sum of contributions from inhomogeneous exchange, uniaxial anisotropy, and magnetic–dipole interaction.

The static Landau–Lifshitz equation in our case has the form

$$\begin{aligned} &m_x\nabla^2 m_y - m_x\nabla^2 m_y = \Lambda^{-2}[m_y h_x^{(m)} - m_x h_y^{(m)}],\\ &m_z\nabla^2 m_x - m_x\nabla^2 m_z - \Delta_B^{-2} m_z m_x = \Lambda^{-2}[m_x h_z^{(m)} - m_z h_x^{(m)}]. \end{aligned} \tag{1}$$

Here $\boldsymbol{m} = \boldsymbol{M}\cdot M_s^{-1}$; the condition $(m_x^2 + m_y^2 + m_z^2) = 1$ is taken into account; $\boldsymbol{h}^{(m)} = \boldsymbol{H}_m/(4\pi M_s)$, $\boldsymbol{H}_m$ is the demagnetization field which is determined by magnetostatic equations. The boundary conditions for Eq. (1) may be written as follows:

$$\begin{aligned} &m_y\left[\alpha'\frac{\partial m_z}{\partial n} - \beta'\boldsymbol{n}(\boldsymbol{m}\cdot\boldsymbol{n})\right] - m_z\alpha'\frac{\partial m_y}{\partial n} = 0,\\ &m_x\left[\alpha'\frac{\partial m_z}{\partial n} - \beta'\boldsymbol{n}(\boldsymbol{m}\cdot\boldsymbol{n})\right] - m_z\alpha'\frac{\partial m_x}{\partial n} = 0,\\ &m_x\frac{\partial m_y}{\partial n} - m_y\frac{\partial m_x}{\partial n} = 0 \quad \text{at } z = \pm t/2. \end{aligned} \tag{2}$$

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Here $\boldsymbol{n}$ is the unit vector along the anisotropy axis; the constants α' and β' characterize the exchange and anisotropy at the film surface; the components of the vector $\boldsymbol{m}$ have to satisfy the conditions $m_x, m_y \to 0$, $m_z \to \pm 1$ at $y \to \mp \infty$. Eq. (2) follow from the equation of motion of magnetic moments on the surface and the fulfillment of the exchange boundary condition [9] for solutions of Eq. (1) on the surface.

To solve system (1) with conditions (2) the polar coordinates for vector $\boldsymbol{m} = \{\sin\vartheta \sin\phi, \cos\vartheta, \sin\vartheta\cos\phi\}$ with the polar axis oriented along the DW normal were introduced. Using the representation

$$\vartheta = \vartheta_0 + \theta(\xi, \zeta), \qquad \phi = \varphi_0(\xi) + \psi(\xi, \zeta),$$

where $\xi = y/\Delta_{\mathrm{B}}$, $\zeta = z/\Delta_{\mathrm{B}}$; $\varphi_0(\xi)$ and ϑ_0 describe the Bloch DW, $\sin\varphi_0(\xi) = 1/(\cosh\xi)$, and $\vartheta_0 = \pi/2$, Eq. (1) may be written as

$$[\hat{O} - \Lambda^{-2}]\theta(\xi, \zeta) = \Lambda^{-2} h_y^{(m)}(\xi, \zeta),$$

$$\hat{O}\psi(\xi, \zeta) = \Lambda^{-2} \sin\varphi_0(\xi) h_z^{(m)}(\xi, \zeta). \tag{3}$$

The operator $\hat{O}$ is determined by the expression

$$\hat{O} = \frac{1}{\Delta_{\mathrm{B}}^2}\left[\frac{\partial^2}{\partial\xi^2} + \frac{\partial^2}{\partial\zeta^2}\right] - \frac{\cos 2\varphi_0(\xi)}{\Delta_{\mathrm{B}}^2}.$$

For solution of the magnetostatic problem the components of the demagnetization field may be represented in the form

$$h_y^{(m)}(\xi, \zeta) = -2\pi \int_{-\infty}^{\infty} \mathrm{d}k \exp\{\mathrm{i}k(\xi - \mathrm{i}\tau)\} \frac{\sinh(k\zeta)}{\sinh(\pi k/2)},$$

$$h_z^{(m)}(\xi, \zeta) = 2\pi\mathrm{i} \int_{-\infty}^{\infty} \mathrm{d}k \exp\{\mathrm{i}k(\xi - \mathrm{i}\tau)\} \frac{\cosh(k\zeta)}{\sinh(\pi k/2)}, \tag{4}$$

where $\tau = t/2\Delta_{\mathrm{B}}$ is the main small parameter of the problem. We consider the case when the material quality factor $Q = K/(2\pi M_s^2)$ is much bigger than unity. This condition was used for the theoretical analysis of a DW internal structure in thin yttrium–iron garnet films [1, 2] whereas samples that were used for applications had, as a rule, very moderate values of $Q \geqslant 1$. The material quality factor in ultrathin metallic magnetic films is also $Q \geqslant 1$ because the surface anisotropy that rotates magnetization from the film plane is caused by magnetic–dipole interaction.

Eqs. (3) and (4) represent the complete formulation of the problem under consideration. The fulfillment of the conditions

$$\left.\frac{\partial\theta}{\partial z}\right|_{z=\pm t/2} = 0, \qquad \left.\frac{\partial\psi}{\partial z}\right|_{z=\pm t/2} = 0$$

at the film surfaces is important for the analysis of the problem in the case $t \ll \Lambda$. The part of the operator $\hat{O}$ that is given by the expression $-\partial^2/\partial\zeta^2 + \cos 2\varphi_0(\xi)$ is the well-known Winter operator [10, 11]. Its spectrum contains two modes which correspond to translational motion of the DW and precession of magnetization inside domains. The solutions of Eq. (1) may be represented as expansions with respect to the modes of spectrum of Winter's operator. The following result for the contribution of the translational mode localized in the vicinity of the DW to the $\theta(\xi, \zeta)$ angle can be obtained:

$$\theta^{(\mathrm{tr})}(\xi, \zeta) \approx -\varepsilon^2 \Theta(\tilde{\zeta}) \sin\varphi_0(\xi),$$

where $\varepsilon = \tau/(2\sqrt{Q}) \ll 1$; $\tilde{\zeta} = \zeta/\tau$; and

$$\Theta(\tilde{\zeta}) = \tfrac{1}{2}[(1 + \tilde{\zeta})^2 \ln(1 + \tilde{\zeta}) - (1 - \tilde{\zeta})^2 \ln(1 - \tilde{\zeta}) - 4\ln(2\tilde{\zeta}) - 2\tilde{\zeta}].$$

The value of $\theta^{(\mathrm{tr})}(\xi, \zeta)$ at $y = 0$ and $z = \pm t/2$ describes the DW twisting. As one can see this contribution is really very small,

$$\theta^{(\mathrm{tr})}(y = 0, z = \pm t/2) \approx \pm\varepsilon^2.$$

The following result can be obtained for the contribution of the precessional mode:

$$\theta^{(\mathrm{pr})}(|y| < t, z = t/2) \approx \tau Q^{-1}[\ln 4 - \pi|\xi|/(2\tau)].$$

The contribution of the translational mode to $\psi(\xi, \zeta)$ is equal to zero because $h_z^{(m)}(y)$ is an odd function and the precessional contribution is given by the expression

$$\psi^{(\mathrm{pr})}(y, z = t/2) \approx -\xi Q^{-1}[1 + \ln(2\tau/\xi)].$$

Thus, the contributions to the DW twisting in ultrathin magnetic films caused by the translational and precessional modes of the DW spectrum are negligibly small. It is easy to show that the standard variational procedure [1] for calculation of the DW twisting gives the same results.

The result obtained above allows to suppose that the DW dynamic in ultrathin magnetic film should correspond to the one of a Bloch DW at least in the case of the stationary motion.

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