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Origin of the force exciting domain wall deformation in a thin magnetic film

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Abstract

The origin of the pinning force acting on Bloch or Néel domain walls in thin magnetic films with a uniaxial anisotropy is discussed. The energy changes are investigated assuming that initially the external magnetic field induces the bulge of the domain wall attended with the pinning of the wall edges. The critical values of the field when the wall moves to a new equilibrium state were determined. The 'magnetic pressure' and the pinning force are calculated from the changes of the wall energy determined for both kinds of domain walls. These results provide a possibility to obtain the contribution of the exchange energy at the wall deformation and to evaluate the influence of this energy on the wall behavior around the magnetic defects. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The aim of this investigation is to describe the density of the domain wall energy in a thin magnetic film with a thickness t when the Bloch or Néel wall changes its shape. We assume that the shape represents a spherical surface between two planes in an external magnetic field less than the critical value for the concrete wall position (Fig. 1). Following the basic ideas in Refs. [1,2] we used the same idealization in the case of Bloch type wall. Then the density of the exchange energy ε_e for the elementary volume with a magnetization d$\boldsymbol{M}$ will be $\mathrm{d}\varepsilon_e = -\boldsymbol{H}_e\cdot \mathrm{d}\boldsymbol{M} = -(2A/M_s^2)\Delta\boldsymbol{M}\cdot \mathrm{d}\boldsymbol{M}$, where $\boldsymbol{H}_e$ and A are the exchange field and the exchange constant, respectively, M_s is the saturation magnetization of the film material [2]. On the other hand, the force acting on an elementary area ds of the domain wall is $f = \varepsilon_e\,\mathrm{d}s = p_e\,\mathrm{d}s$. The 'magnetic pressure' p_e provokes the change of the radius of curvature $1/R$ until the internal field balances the pressure action. The surface density of the wall energy $\sigma = \sigma_0 + (1/R)\partial\sigma/\partial(1/R) + O^2$ is built from the energy of nondeformed state σ_0 which includes independent of R terms, the energy of deformed state (second term) and the term of second order O^2. In

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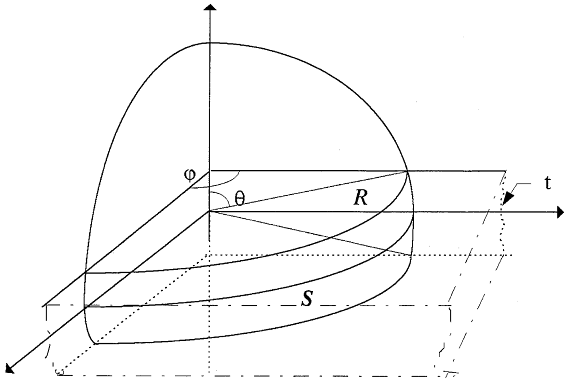

Fig. 1. Coordinate system for the bulged domain wall.

spherical coordinates the expression for the entire exchange energy transforms as

$$\varepsilon_e = -\boldsymbol{H}_e \cdot \boldsymbol{M} = -\frac{2A}{M_s}\boldsymbol{m} \cdot \Delta \boldsymbol{M}, \tag{1}$$

where $\boldsymbol{m} = \boldsymbol{M}/M_s$ is the relative magnetization and

$$\begin{aligned}\Delta \boldsymbol{M} = &\left\{\frac{2}{r}\frac{\partial M_r}{\partial r} + \frac{\partial^2 M_r}{\partial r^2} - \frac{2M_r}{r^2} - \frac{2M_\theta}{r^2}\cot\theta\right\}\boldsymbol{e}_r \\ &+ \left\{\frac{2}{r}\frac{\partial M_\theta}{\partial r} + \frac{\partial^2 M_\theta}{\partial r^2} - \frac{M_\theta}{r^2 \sin^2\theta}\right\}\boldsymbol{e}_\theta \\ &+ \left\{\frac{2}{r}\frac{\partial M_\varphi}{\partial r} + \frac{\partial^2 M_\varphi}{\partial r^2} - \frac{M_\varphi}{r^2 \sin^2\theta}\right\}\boldsymbol{e}_\varphi.\end{aligned} \tag{2}$$

2. Theoretical background

We determined the additional term of the exchange field as a result of a deformed Bloch type wall. In this case the components of the magnetization are

$$\boldsymbol{M} = M_s\left(0, \pm\,\mathrm{sech}\left(\frac{R-r}{\delta_B}\right), \tanh\left(\frac{R-r}{\delta_B}\right)\right), \tag{3}$$

where $\delta_B = \sqrt{A/K_u}$ is the Bloch wall width and K_u is the constant of an induced uniaxial anisotropy. From Eqs. (2) and (3) we determined the components of the exchange field at $r = R$, $\sin\theta \approx 1 - t/2R$ and $\sin^2\theta \approx 1 - (t/R)^2$

$$\boldsymbol{H}_e = -\frac{4A}{M_s} \times \left\{\frac{1}{R^3}\left(\frac{1}{1-(t/2R)}\right), \frac{1}{2}\left(\frac{1}{\delta_B^2} + \frac{1}{R^2 - t^2}\right), \frac{1}{\delta_B R}\right\}. \tag{4}$$

If $R \to \infty$, then the components $H_r \to 0$ and $H_\varphi \to 0$. The second component of $\boldsymbol{H}_e$ in (4) is not equal to 0 and gives a contribution in σ_0.

From Eqs. (3) and (4) we can obtain the additional 'magnetic pressure' $p_e = -\boldsymbol{H}_e\,\mathrm{d}\boldsymbol{M}$ on the wall element ds, varying R in the exchange energy and excluding the energy of nondeformed Bloch wall

$$\begin{aligned}p_e = &-\frac{4A}{\delta_B^2}\int_a^b \frac{\tanh^2 x}{r\cosh^2 x}\,\mathrm{d}r \\ &+ 2A\int_a^b \frac{\tanh x}{r^2 \sin^2\theta \cosh^2 x}\,\mathrm{d}r \\ &- \frac{4A}{\delta_B^2}\int_a^b \frac{\tanh x}{r\cosh^4 x}\,\mathrm{d}r \\ &- 2A\int_a^b \frac{\tanh x}{r^2 \sin^2\theta \cosh^2 x}\,\mathrm{d}r\end{aligned} \tag{5}$$

where $a = R - \delta_B/2$, $b = R + \delta_B/2$ and $x = (R-r)/\delta_B$. The sum of the second and the fourth term is equal to zero. The value of $1/R$ is nearly constant at $R \gg \delta_B$. Then

$$\begin{aligned}p_e &= -4A\int_a^b \frac{\sinh^2 x + 1}{r\delta_B^2 \cosh^4 x}\,\mathrm{d}r \\ &= 4A\int_a^b \frac{1}{r\delta_B}\,\mathrm{d}\tanh x \cong -\frac{4A}{R\delta_B}k, \quad k = 0.924.\end{aligned} \tag{6}$$

The expression (6) includes the part of the exchange energy depending on $1/R$ which adds to σ_0 for 180° domain wall. At $k = 1$ our result is similar to the result of the other authors [2].

The force f acting on the wall element ds is $f = -(4A/R\delta_B)k$ ds and the additional term in σ is

$$\sigma_e = -\frac{1}{2}\int_a^b \boldsymbol{H}\cdot\boldsymbol{M}\,\mathrm{d}r$$
$$= 2A\int_a^b \frac{\mathrm{d}r}{r^2\cosh^2 x} + 2A\int_a^b \frac{\tanh^2 x\,\mathrm{d}r}{r^2} = \frac{2A\delta_B}{R^2-\delta_B^2}, \tag{7}$$

where we suppose $\sin\theta \approx 1$. In the presence of magnetic or other local defects it is possible that $1/R \sim 1/t$, then the expression (7) gives a significant supplement to the exchange energy.

The behavior of the exchange energy for Néel domain wall can be treated similarly. In this case div $\boldsymbol{M} \neq 0$ and there are 'magnetic charges' in the film volume, which induce an augmentation in the magnetostatic energy of the domain wall. Besides the domain wall deformation increases the magnetostatic energy. The pressure $p_e = -\boldsymbol{H}_e\cdot \mathrm{d}\boldsymbol{M}$ gives an auxiliary energy term similar to the expression (5). After integrating the procedure we could find f and σ_e changing δ_B with δ_N.

3. Results and discussion

Using the characteristic length of the film material

$$l = \frac{4\mu_0\sqrt{AK_u}}{M_s^2} \tag{8}$$

and describing the domain wall width with the relevant expressions we found the pinning forces f_B and f_N for Bloch and Néel domain wall, respectively:

$$f_B = -k\frac{M_s^2 l_B}{\mu_0 R}\,\mathrm{d}s, \quad \text{where } l_B = \frac{4\mu_0\sqrt{AK_u}}{M_s^2}, \tag{9}$$

$$f_N = -k\frac{M_s^2 l_N}{\mu_0 R}\,\mathrm{d}s,$$
$$\text{where } l_N = \frac{4\mu_0\sqrt{A(K_u+(M_s^2/\mu_0))}}{M_s^2}. \tag{10}$$

The exchange field determining the pinning forces in both cases is

$$H_{Be} = -\frac{M_s l_B}{2\mu_0 R} \quad \text{for Bloch wall,} \tag{11}$$

$$H_{Ne} = -\frac{M_s l_N}{2\mu_0 R} \quad \text{for Néel wall.} \tag{12}$$

The materials for thin magnetic films with uniaxial magnetic anisotropy in the film plane is distinguished with the small characterizing length. Therefore, the external magnetic field $H \ll M_s/\mu_0$ will change the wall from plane to bulging shape. The similar effect of a deformation can be observed experimentally in the areas with structural and magnetic defects where the domain wall holds back during the motion. The radius of curvature of the domain wall is determined from Eqs. (11) and (12) as $1/R \approx \mu_0 H/M_s l_{B,N}$. If the magnetic field interval for the initial part of the magnetization curve is known, the average value of the radius can be obtained as

$$\bar{R} \approx \frac{M_s}{\mu_0 H_{R\,max}}\, l_{B,N}. \tag{13}$$

For typical values $l = 10^{-8}$–10^{-9} m, $M_s =$ 0.5–1 T and $H_{R\,max} = 6$–8 A/m we obtain $R = 10^{-3}$–10^{-4} m. Introducing these data in Eq. (6) we determined the additional surface energy σ_e of the order of 10^{-9}–10^{-10} J/m^2. This value is a few orders less than $\sigma_0 \approx 10^{-5}$ J/m^2 and can be neglected. But the contribution of σ_e will be essential at $R \approx t$.

Analyzing the static of the deformed domain wall [3] we suppose the value of the parameter $\eta = f/\sigma_0 \approx 0.1$–$0.2$. Some concrete results are obtained at $\eta = 0.147$. The results of the other authors ($\eta = 0.116$ for $Ni_{0.5}Zn_{0.5}Fe_2O_4$ and $\eta = 0.1368$ for YIG) are in the same interval [4,5]. To explain the different value of the parameter η as a result of the changes of the exchange energy must be taken into account the second radius of curvature $1/R_2 \approx 1/t$ (Fig. 2).

Thus we can get similar expressions for f and σ where R is replaced with $R_2 \approx t$. In our calculations we used the analytical expression for Bloch

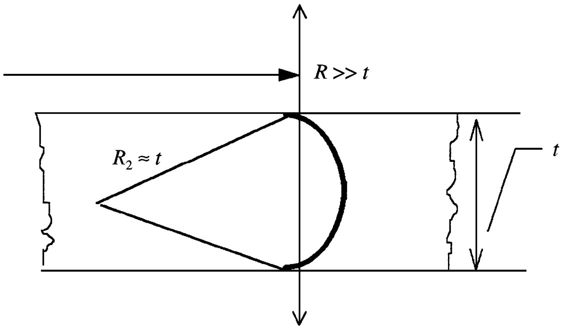

Fig. 2. Cross-section of the film in the case $R_2 \approx t$.

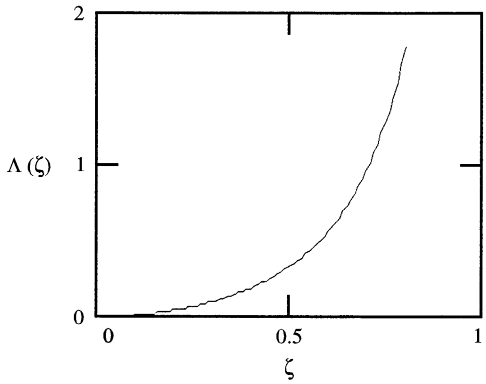

Fig. 3. The relative wall energy versus the parameter ζ.

and Néel walls but in the last case ($t \approx \delta = 10^{-7}$) this is not justifiable [7]. In this case the pinning force acting on the bulged wall may be explained with the other terms of the wall energy. The result for the additional energy due to $1/R_2$ may be used to evaluate the field around spherical magnetic defects with a size of the order of thin film thickness when the exchange energy $\sigma_e \sim \sigma_0$. The relative energy Λ of the deformed wall versus nondeformed wall is a function of the rate ζ between the wall width and the radius of curvature (Fig. 3):

$$\Lambda(\zeta) = \frac{\sigma'}{\sigma_0} \approx \frac{\delta}{R^2 - \delta^2}\sqrt{\frac{A}{K_u}} = \frac{\delta^2}{R^2(1-(\delta^2/R^2))} = \frac{\zeta^2}{1-\zeta^2}, \tag{14}$$

where $\delta = \delta_B$ or $\delta = \delta_N$. The parameter $\zeta = \delta/R$ shows that the surface energy increases sharply at a small radius of the curvature.

The influence of the domain wall deformation on the speed of wall motion is measured indirectly in Refs. [2,6]. To neglect this influence on the experimental results for nickel ferrite the thickness of the sample might be less than 100 μm and the applied field should not exceed 20 A/m. Similar considerations are applied to YIG [8].

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References

[1] H.L. Huang, J. Appl. Phys. 40 (1969) 855.
[2] T.H. O'Dell, The Dynamics of Magnetic Bubbles, Domain and Domain Walls, Macmillan, New York, 1981.
[3] I.G. Antonov, L.P. Vatskitchev, Phys. Stat. Sol. (a) 153 (1996) 173.
[4] M.A. Escobar, L.F. Magaña, R. Valenzuela, J. Appl. Phys. 53 (1982) 2692.
[5] M.A. Escobar, R. Valenzuela, L.F. Magaña, J. Appl. Phys. 54 (1983) 5935.
[6] J.K. Galt, Bell Syst. Tech. J. 33 (1954) 1023.
[7] A. Aharoni, J. Appl. Phys. 47 (1976) 3329.
[8] A. Harper, R.W. Teale, J. Phys. C 2 (1969) 1926.