Journal of Magnetism and Magnetic Materials 374 (2015) 600–606

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Numerical studies of micromagnetic configurations in stripes with in-plane anisotropy and low quality factor

B.N. Filippov [a,b], M.N. Dubovik [a,b,*], V.V. Zverev [b]

[a] Institute of Metal Physics UB RAS, S. Kovalevskoy Str., 18, 620990 Yekaterinburg, Russia
[b] Ural Federal University, Mira Str., 19, 620002 Yekaterinburg, Russia

ARTICLE INFO

Article history:
Received 28 June 2014
Received in revised form
18 August 2014
Available online 10 September 2014

Keywords:
Micromagnetic simulation
Cross-tie domain walls
C-shaped domain walls
Permalloy films

ABSTRACT

Magnetization distributions and energy of 180-degrees domain walls in a stripe-film were investigated over a wide film thickness range. Three-dimensional numerical simulations are performed. Two kinds of transitions between stable domain wall configurations were obtained: from Néel walls to cross-tie walls and from cross-tie walls to asymmetric Bloch (C-shaped) walls. The latter kind of transition was investigated for the first time. The transition from the two-dimensional cross-tie structure to the three-dimensional one during the rise of the film thickness was demonstrated.

1. Introduction

Researchers have been paying a great attention to magnetic films with in-plane anisotropy and low quality factor $Q = K/2\pi M_S^2$ (M_S is the film saturation magnetization and K is the anisotropy constant). Information storage devices were developed based on those films evaporated on cylindrical surfaces with a small radius [1]. Nowadays interest increases in those films investigation. That is accounted for by both development of new film-based memory types with the extra high capacity, for instance "racetrack memory" [2,3], and a hope to reveal new physical properties. The hope is related to the new methods of films production and experimental investigation, and the theoretical numerical methods great development.

The film thickness was found to influence on the micromagnetic structures and thus on the film magnetization reversal. It was established long ago [4] that decreasing the film thickness results in arising a new type of domain wall: the Néel one. The situation was initially described as follows. At the film thickness $b > b_N$ one-dimensional (the magnetization vector $\mathbf{M}$ direction depends on one coordinate) Bloch walls were assumed to exist with the magnetization directed normally to the film surface in the wall center. At $b < b_N$ one-dimensional Néel walls are stable with the magnetization always parallel to the film surface. Both the one-dimensional walls possess symmetric structure relative to the wall center surface, with that surface being a plane. A domain wall center surface is the level surface $m_z = 0$ if the z axis is directed along the easy axis, where $\mathbf{m} = \mathbf{M}/M_S$ is a normalized magnetization. Thus the walls mentioned will be referred to as symmetric Néel and symmetric Bloch walls. The value b_N has been named as a Bloch–Néel transition thickness.

However Huber, Smith and Goodenough [5] observed the completely new cross-tie domain wall using the powder method. Later the cross-tie walls were also observed using the electron microscopy methods [6]. A cross-tie wall has the complicated structure with alternating vortexes and antivortexes on the film surface. Its energy was calculated to be lower than a Néel wall one in [7] but it was the case for all b values and the two different walls energies ratio was always equal to 0.6 independent on the film material parameters. That made the results of [7] strange. Notwithstanding many observations appeared of both Néel and cross-tie walls existing in the same conditions (see, for example, [8] and the references there). Attempts to improve the results of [7] using the more accurate (for that time) computation methods failed to clarify the matter thought gave new details about Néel walls [9–11]. There were also numerical simulations of a cross-tie wall structure [12,13] at a fixed b value.

Theoretical investigations [14–16] were more successful to reveal two points on the film thickness axis (instead of one b_N as in the previous theoretical concepts) where transitions occur between the different domain wall types. That agreed with the experimental results [17]. Let's refer the points mentioned as b_L and b_R (left and right, given the thickness increases while moving along the axis from left to right). b_L corresponds to the transition from Néel walls to cross-tie ones, and was obtained to be much

* Corresponding author at: Institute of Metal Physics UB RAS, S. Kovalevskoy Str., 18, 620990 Yekaterinburg, Russia.
E-mail addresses: filbor@imp.uran.ru (B.N. Filippov), dubovik@imp.uran.ru (M.N. Dubovik), vvzverev49@gmail.com (V.V. Zverev).

http://dx.doi.org/10.1016/j.jmmm.2014.09.011
0304-8853/

smaller than b_N. The thickness b_R was initially interpreted as the thickness above which symmetric Bloch walls became energetically favorable as compared with cross-tie ones. Thus cross-tie walls are stable at $b \in (b_L, b_R)$. However b_R determination in [14–16] has to be confessed incorrect now, because no one-dimensional symmetric Bloch walls exist in magnetically soft films according to the results of more recent numerical calculations [18–20]. Instead asymmetric Bloch walls (also referred to as C-shaped walls) and asymmetric Néel walls exist. The transition from the asymmetric domain walls to cross-tie walls was investigated in [19] but it was obtained that without applying a magnetic field the cross-tie wall energy was always smaller than the Néel wall one as it was in [7]. That again disagreed with the experimental data [8,17], and perhaps related to insufficiency of the Ritz method or of the trial functions used in [19].

There is one more point to be mentioned. On the one hand the one-dimensional model seems to be sufficient to study Néel walls in films much thinner than b_R. On the other hand according to [21] such walls can possess non-one-dimensional structure. Although the difference may be small at large computational cells number (see the next section), making no allowance for that may lead to unstable results. In this connection remember that according to [22] all one-dimensional magnetization distributions are unstable (see also [23], p. 163–164).

According to the mentioned above a clear picture of a one or another stable or metastable domain wall type existence at the different film thicknesses has not been obtained yet. We insist on that it is necessary to use the same calculation method for all the domain wall types to obtain such a picture. Nowadays three-dimensional calculation is available with making allowance for all necessary interactions including the long-range dipole–dipole one. The transition corresponding to b_L had already been investigated in such a way [24]. Here the results of the domain walls structure numerical investigations in the wider thickness range will be reported including the transition corresponding to b_R. This three-dimensional calculation results will be compared with the experimental observations of the cross-tie structure period dependence on the film thickness [25] (p. 424), and b_L and b_R values dependence on M_S and K [17]. At last it will be shown that the vortex and antivortex magnetization distributions cross-cutting the film in cross-tie walls became non-cross-cutting in asymmetric Bloch walls. This result has not been obtained yet theoretically or experimentally.

2. Simulation details

The simulations were performed using the OOMMF micromagnetic package [26]. A stripe-film fragment in the form of a parallelepiped is considered. The film surface is parallel to the xz plane and the easy axis is directed along the z axis (see Fig. 1). Thus let's denote the film width, thickness and length as a, b and c. The film magnetic state corresponds to two domains separated by a 180-degrees domain wall. To obtain the wall magnetization distribution the film energy minimization is performed with the condition for the magnetization vector $|\mathbf{M}| = M_S$. The total energy has the following form:

$$E = \int_0^a dx \int_0^b dy \int_0^c dz \left\{ \frac{A}{M_S^2} \nabla^2 \mathbf{M} + \frac{K}{M_S^2}\left(M_x^2 + M_y^2\right) - \frac{1}{2}\mathbf{M}\mathbf{H}^{(m)} \right\} \quad (1)$$

where the first, second and third terms in the integrand are the exchange, anisotropy and dipole–dipole interactions energy densities correspondingly. A is the exchange parameter and the stray field $\mathbf{H}^{(m)}$ is determined as follows:

$$\mathbf{H}^{(m)} = -\nabla \varphi, \quad \varphi(x,y,z) = \int_0^a dx' \int_0^b dy' \int_0^c dz' \mathbf{M}(x',y',z')$$

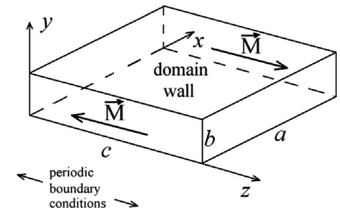

Fig. 1. Geometry of the problem. The considered stripe-film fragment and the domains magnetization directions are shown. The z axis is the easy magnetization axis and the y axis is directed normally to the film surface. The magnetization distribution $\mathbf{M}$ is treated as a function of the all three coordinates.

$$\nabla' \frac{1}{\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}}. \quad (2)$$

The features of implementing (2) in numerical calculations like performed here can be found in [27–29]. In brief, the computational region is divided by a grid into cubic cells, with each cell magnetization being considered uniform. After that the stray field is expressed as a convolution of the cells magnetization array with an interaction matrix determined by the grid and fast Fourier transforms are used to accelerate the calculation. If not stated otherwise, the following material parameters values are used: $A = 1.3 \times 10^{-6}$ erg/cm, $M_S = 800$ G, $K = 10^3$ erg/cm^3. The computational cells are cubic in shape, with an edge dimension equal to 5 nm.

The approach to cross-tie walls investigation is analogous to the one used in [24]. Cross-tie walls tend to possess periodic structure according to the existent experimental data and theoretic conceptions. Bearing that in mind one can use periodic boundary conditions applied along the easy axis direction (the z axis) to decrease the cells number and exclude the film edges effect. The periodic boundary conditions presence alters the exchange and magnetostatic energy calculation, namely, the magnetostatic interaction matrix is calculated in the different way [29]. Minimizing the energy of the initial $\mathbf{M}$ distribution roughly resembling a cross-tie wall structure one can obtain a stable equilibrium configuration for the fixed period c value. The initial distributions were created in such a way that the simulation region contains one vortex–antivortex pair (see Fig. 2). It is convenient to consider a domain wall energy surface density $\gamma_m = E_m / b \times c$. Here E_m is the equilibrium value of E and the energy is divided by b because as a rule all the interactions energies grow with increasing the film thickness and it is impossible to judge from E_m values how an interaction relative impact changes with the thickness change. With increasing the period c a cross-tie wall dependence $\gamma_m(c)$ converges asymptotically to the value corresponding to the Néel wall with the $\mathbf{M}$ distribution homogeneous along z. At small c values the wall energy density grows sharply due to the exchange energy increasing. In the intermediate c region the $\gamma_m(c)$ curve can have a minimum and that really takes place for the film thickness b larger than a certain value. This thickness value is b_L. The c value corresponding to the minimum mentioned is the "natural" cross-tie wall structure period T. The cross-tie wall would have this period in a film without any pinning centers and far from the film edges along the easy axis. The reader is referred to [24] for more details about T determination. One must obtain a new T value each time solving the problem with new parameters (the film thickness, material parameters, etc). If not stated otherwise, the data reported below corresponds to $c = T$. At $b < b_L$ the $\gamma_m(c)$ curve does not possess a minimum at any c value. In this case it is concluded that a pure Néel wall is stable at that film thickness.

As already mentioned the other domain wall types can exist in thicker films, namely asymmetric Bloch and Néel walls.