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Role of anisotropy on the domain wall properties of ferromagnetic nanotubes

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ABSTRACT

In this paper we investigate the role of magneto-crystalline anisotropy on the domain wall (DW) properties of tubular magnetic nanostructures. Based on a theoretical model and micromagnetic simulations, we show that either cubic or uniaxial magneto-crystalline anisotropies have some influence on the domain wall properties (wall size, propagation velocity and energy barrier) and then on the overall magnetization reversal mechanism. Besides the characterization of the transverse and vortex domain wall sizes for different anisotropies, we predict an anisotropy dependent transition between the occurrence of transverse and vortex domain walls in tubular nanowires. We also discuss the dynamics of the vortex DW propagation gradually increasing the uniaxial anisotropy constant and we found that the average velocity is considerably reduced. Our results show that different anisotropies can be considered in real samples in order to manipulate the domain wall behavior and the magnetization reversal process.

1. Introduction

Because of their unique properties the study of *magnetic nanotubes* (MNs) has become recently an interesting field of research, both from experimental [1–7] and theoretical [8–14] standpoints. MNs have been synthesized with a variety of methods [1–7] and they has been further proposed for biotechnological applications [4–6]. It has been theoretically predicted that, depending on the cross section, the magnetization reversal process of MNs is mediated by the propagation of either transverse or vortex-like domain walls [8,9,12]. Magnetic *domain walls* (DWs), which separate regions of opposite magnetization, have been investigated over many years, and are quite important entities in the field of magnetism, not just for the basic physical properties they show, also for its promising applications as magnetic memory elements [15], DW logic devices [16], or DW conduits for the manipulation of functionalized magnetic nanoparticles [17]. Within the available literature, DWs have been mostly studied in nanowires of rectangular cross section (or nanostrips) where *transverse* and *vortex* domain walls have been identified [18,19]. In a similar way, magnetic nanotubes also show these two main types of domain walls [8,9,12] but due to the cylindrical symmetry the vortex domain wall (VDW) is essentially different than that of the nanostrip. Indeed, the VDW in MNs resembles more to a transverse wall in a nanostrip, which can be obtained by unrolling the tube into a flat strip [14].

Vortex and transverse domain walls (TDW) have been further investigated in circular nanowires [20–23], and it has been shown that, since the propagation of a transverse wall is accompanied by a gyroscopic motion [22], the VDW moves faster than the TDW. However, in circular nanowires the propagation of a VDW has a singularity (or Bloch point) in the axis leading to the formation of "magnetic drops" [24]. We remark that this behavior is completely avoided in the nanotube, making the propagation of the VDW simpler, predictable and with high stability [12,14].

In this paper we present a detailed analysis of the role of magnetic anisotropy, describing the fact that there are preferential crystallographic orientations for the magnetization [25], on the behavior of both kinds of domain walls and reversal process discussed above. Besides dipole–dipole and exchange interactions, we consider here cubic and uniaxial anisotropy contributions. We present quantitative calculations for the anisotropy dependence of the vortex and transverse DW width, energy barriers for DW magnetization reversal and DW velocity. We will show the dependence with anisotropy of the magnetization reversal phase diagram, showing the preferred DW type as function of the geometrical parameters. We also show that, provided the tube length is greater than the domain wall width (w), and if there is some anisotropy present in the system, the wall width depends on the cross section of the tube, the exchange length and the anisotropy constant. We also provide an analysis based on micromagnetic simulations of the domain wall velocity for different uniaxial anisotropy constants. The paper is organized as follow: in Section 2 we present the theoretical basis of our work, whereas our results are presented and discussed in Section 3. Section 4 summarizes our main findings.

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2. Theory

2.1. System and notation

We start with the definition of our system. We characterize the nanotubes by their external and internal radii, R and R_i respectively and height or length L. For the following discussions, it is usual to define a form factor $\beta = R_i/R$, such that $\beta = 0$ is a solid cylinder, and $\beta \approx 1$, a very narrow tube. We will use the exchange length of the magnetic material, $L_x = (2A/\mu_0 M_s^2)^{1/2}$, as a natural measure of lengths. Here A is the exchange constant [26], M_s is the saturation magnetization and μ_0 the permeability of free space. We further use the following notation for the normalized dimensionless anisotropies: $\kappa_{u,c} = 2K_{u,c}/(\mu_0 M_s^2)$, where K_u and K_c are the uniaxial and cubic magneto-crystalline anisotropy constants respectively. We remark that our results are most appropriate for nanotubes with small thickness, since the model explained below do not consider any dependence of the magnetization on the radial coordinate.

2.2. Model for transverse and vortex domain walls

Transverse and vortex domain walls have been previously described in isotropic systems [8] where it is assumed that the tubes are large enough so that coherent rotation can be left out of consideration. Magnetization reversal takes places with the nucleation and propagation of both kind of DWs (TDW and VDW). The occurrence of these magnetization reversal processes depends mainly on the geometry [8]; for systems with small radius transverse DWs are energetically favorable since the exchange energy overcomes dipolar effects. For nanotubes with bigger radius, dipolar effects becomes more important and vortex-like DWs are preferred [8]. Here we use the same model for the domain wall magnetization which is explained below for completeness, and we include the effect of uniaxial and cubic magneto-crystalline anisotropies. We consider head-to-head DWs which can be described with the following magnetization vector (Fig. 1):

$$\mathbf{M}/M_s = \mathbf{m}(z) = \sin\Theta(z)\hat{\mathbf{p}} + \cos\Theta(z)\hat{\mathbf{z}}, \tag{1}$$

where z is the axial coordinate, $\hat{\mathbf{p}}$ is a unitary vector perpendicular to $\hat{\mathbf{z}}$ which can represent both kind of DWs; using $\hat{\mathbf{p}} = \hat{\boldsymbol{\phi}}$ we have a vortex wall, while choosing $\hat{\mathbf{p}} = \hat{\mathbf{x}}$, a transverse wall is obtained. We will describe the DW magnetization with two parameters, the position of the DW center, z_0, and the DW width w. Then, the polar angle of the magnetization is given by $\Theta(z) = 0$ if $z < z_0 - w/2$ (below the DW), and $\Theta(z) = \pi$ if $z > z_0 - w/2$ (above the DW). Inside the wall (for $z_0 - w/2 < z < z_0 + w/2$) the polar angle is given by [8]:

$$\Theta(z) = \pi\left(\frac{z - z_0}{w} + \frac{1}{2}\right). \tag{2}$$

2.3. Magnetic energy for transverse and vortex domain walls

Both kinds of domain walls see Fig. 1 can be characterized by the simple mathematical expressions discussed in the previous section. The next step is to calculate the total micromagnetic energy for both DW configurations, minimize the energy to find the DW width, and then to evaluate the energy barrier for each reversal mode. The magnetic energy can be calculated using the continuous theory of ferromagnetism [26], where the total energy is given by the exchange, dipolar, anisotropy and Zeeman contributions. Exchange and dipolar terms have been calculated before [8] and we quote it here for completeness. The exchange energy for the transverse (T) and vortex (V) walls are respectively given by:

$$E_{ex}^{T} = \frac{\pi^3 A R^2}{w}(1-\beta^2) \tag{3}$$

and

$$E_{ex}^{V} = \pi A w \ln\left(\frac{1}{\beta}\right) + \frac{\pi^3 A R^2}{w}(1-\beta^2). \tag{4}$$

The dipolar contribution can be expressed as [8]:

$$E_d^{T,V} = \pi \mu_0 M_s^2 R^2 \int_0^\infty \frac{dq}{q^2} [J_1(qR) - \beta J_1(\beta q R)]^2 \times (g_s^{T,V} + g_v^{T,V}), \tag{5}$$

where $g_s^{T,V}$ and $g_v^{T,V}$ stands for the surface and volumetric dipolar contributions, either for the transverse and vortex modes, and are given by [8]

$$g_s^{T} = \frac{q^2 w^2/2\pi^2}{1+q^2w^2/\pi^2}\left(\frac{qw}{2} + \frac{1+e^{-qw}}{1+q^2w^2/\pi^2}\right) + g_s^{V}, \tag{6}$$

$$g_s^{V} = 1 + e^{-qL} - \frac{e^{-q(L-z_0)} + e^{-qz_0}}{1+q^2w^2/\pi^2}\cosh\left[\frac{qw}{2}\right], \tag{7}$$

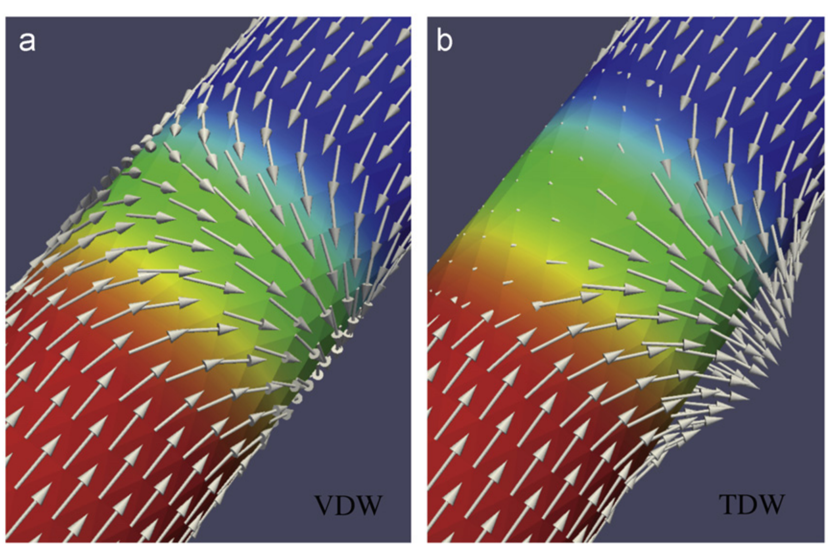

Fig. 1. Illustration of the magnetic structure of (a) a vortex domain wall and (b) a transverse domain wall. We clearly see that inside the VDW the magnetization follows the cylindrical symmetry while the magnetization inside the TDW points along a well defined direction.