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ORIGINAL PAPER

# Role of Perpendicular Anisotropy in the Zigzag Domain Wall Structure in Thin Magnetic Films

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**Abstract** We investigate apparently zigzag domain walls in ultrathin magnetic films and calculate the total energy in zero applied field considering anisotropies in the second-order approximation. We discuss the change in zigzag wall morphology and scale as a function of the dipolar length and the total energy depend on film parameters exclusively anisotropy constants, crystallographic orientation and film thickness for a given dipolar length. We explain also the role of the second-order anisotropy in the total energy and the dynamics response of the in-plane magnetization for a given dipolar length. We use some constants in connection with experimental data reported for amorphous TbCo films grown in external in-plane magnetic field by high-frequency ion sputtering and for MnAs on GaAs films.

**Keywords** Thin film · Perpendicular anisotropy · Domain walls and domain structure

## 1 Introduction

A novel type of domain walls in thin films and two-dimensional magnetic materials has attracted much attention mainly due to aspects related to information storage. Magnetic domain walls in thin films are low-dimensional objects that separate regions with uniform magnetization [1]. Magnetic anisotropy plays a key role which is closely related to the utilization of the direction of magnetization for new technologies.

Recent experiments [2, 3] have observed a zigzag domain wall structure in amorphous rare-earth (RE)–transition metal (TM) films and MnAs-on-GaAs systems which are varied strongly with film thickness as discussed by earlier workers experimentally [4–8] and theoretically [9–11]. The observed domain wall structures can arise from a balance between the exchange, dipolar and anisotropy energies. In this context, understanding and controlling domain wall patterns are important, because they allow to extract information about magnetization and anisotropy.

It is of interest to look at the magnetostatic solution for the total energy of the pattern in zero applied field considering anisotropies in the second-order approximation.

We would like, however, to discuss the in-plane magnetization component of magnetization in the framework of competing magnetostatic, domain wall, first- and second-order contributions of the perpendicular anisotropy for a given dipolar length. One can therefore expect to gain additional insight into these properties in thin films. Analysis of equilibrium zigzag wall structures was based on the present work on calculations of the zigzag wall period considering the classical parameter, called the dipolar length $P_o = \frac{\sigma_\omega}{2\pi M_0^2}$ [12], where $M_0$ is the saturation magnetization and $\sigma_\omega$ is the wall energy density per unit area. $P_o$, which is dependent on the film thickness, induced magnetic anisotropy changes.

We use a continuum model, which is justifiable because the zigzag walls are so large compared with the lattice spacing, and present our theoretical analysis to examine how dipolar length, film thickness and second-order anisotropy can stabilize the zigzag wall period, the total energy and the in-plane magnetization.

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## 2 Basic Expressions

In a previous work [13], we calculated the magnetostatic energy as functions of the zigzag period, $P$, and the film thickness, $L$, for an equilibrium configuration in the absence of external magnetic field. The film is taken as an infinite slab parallel to the $(xy)$ plane with thickness $L$ along the $z$ coordinate. The geometry of the film and its two-dimensional partition were shown in this work. Provided that the domain wall size is large compared with the domain size, we have found that the zigzag period is varied with the film thickness in which there are approximately three different range of values of the film thickness. The zigzag walls become stable with increasing film thickness above about 200 nm [13]. Engel-Herbert et al. [3] reported that a 300-nm-thick film exhibits fully developed zigzag walls. When the thickness of the films grows, the perpendicular anisotropy is reduced in films, and magnetostatic energy becomes important, inducing the magnetization to develop an in-plane component in which domain walls become wider [14].

Given a regular array of zigzag patterns in zero applied field and assuming that the thickness of the domain width is negligible compared against $P$ (zigzag period) in which the exchange energy would be very small and thus ignored, within these assumptions, the total energy of the magnetized film is represented by the sum of magnetostatic energy, anisotropy energy and wall energy as follows [15]:

$$E = \left\{ \left(\frac{2}{\pi}\right)^5 \frac{2\pi M_0^2 L}{\delta} \sum_{\substack{n=1 \\ (\text{odd})}}^{\infty} \frac{1}{n^5} \left(1 - e^{-n\pi\delta}\right) - (K_1 + 2K_2) L + \sigma_\omega \frac{L}{P} \right\} \sin^2\theta + K_2 L \sin^4\theta + (K_1 + K_2) L + K_o \tag{1}$$

where we define $\delta = L/P$; the experimental value of $\delta$ is $\cong 10^{-3}$ for the films of interest [2]. $K_1$ and $K_2$ denote the first- and second-order terms of anisotropy constant. The first term of the curly brackets, which is the magnetostatic energy, is found by expanding the magnetic potential in a Fourier series and matching to the boundary conditions as explained in a previous work [13]. The nature of zigzag walls is described in some detail together with the variation in the dipolar length, and also the local magnetization vector inside the walls may be tilted at an angle $\theta$ with respect to the plane normal ($z$-axis). The minimization of the total energy with respect to $P$ and $\theta$ will give the real equilibrium conditions. The dependence of the equilibrium zigzag wall period as a function of the dipolar length is shown in Fig. 1. As can be seen, the zigzag wall period grows linearly with

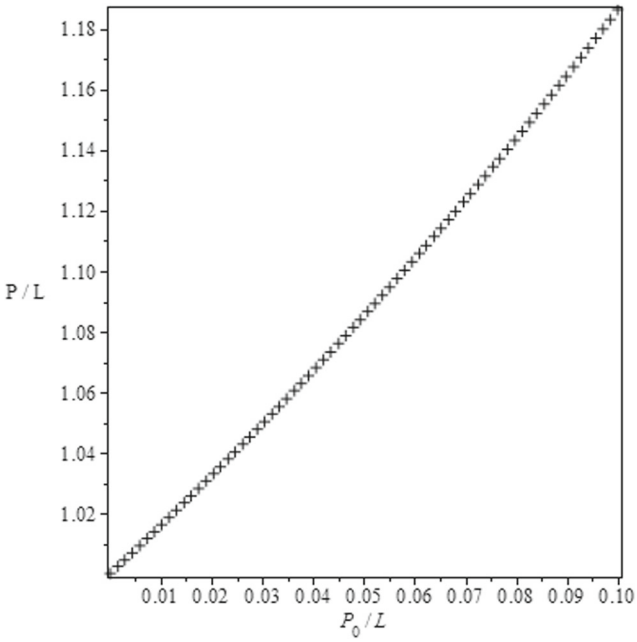


**Fig. 1** Zigzag period vs dipolar length

increasing dipolar length. Zigzag walls in which the magnetization stays inside the $(yz)$ plane. If $K_2 \neq 0$, the stable magnetization angle $\theta$ can be obtained as follows:

$$\theta = \sin^{-1} \left\{ \frac{(K_1 + 2K_2) L - M_0^2 L G(\delta)}{2K_2 L} \right\}^{1/2} \tag{2}$$

where $G(\delta) = a + b\delta + c\delta^2 + d\delta^3 + e\delta^3 \ln \pi(\delta)$ and the coefficients $a = \frac{2\pi}{3}$, $b = -\frac{28\xi(3)}{\pi^2} + 4$, $c = \frac{4\pi}{3} - 4$, $d = -\frac{8k}{3} - \frac{25}{9} + \frac{4\gamma}{3} + \frac{4\ln\pi}{3}$, $e = \frac{4}{3}$, $k \cong 0.635$, and $\xi$ and $\gamma$ are the Riemann zeta function and Euler constant with $\xi(3) \cong 1.202$ and $\gamma \cong 0.577$, respectively. Figure 2 shows the total energy as a function of the angle $\theta$ for given $P_o/L = 10^{-3}$ and $\eta = 0.3$, where $\eta$ is defined by $K_2/K_1$, for different film thicknesses, assuming $M_o = 400\text{emu/cm}^3$ and $K_1 \approx 10^6\text{erg/cm}^3$ [2, 3]. For $\theta = \pi/2$, the energy is not equal to zero. Although it is not shown here, the total energy increases when the $P_0/L$ and $\eta$ increase. When $\theta$ approaches zero, the energy increases very rapidly. The same results are presented in a different way in Fig. 3, where the energy is plotted versus the film thickness, $L$, for various values of $\theta$. The total energy, as long as $\theta$ exceeds 5°, varies linearly with $L$. As has already been seen, these curves overlap at about $L = 15\text{nm}$. On the other hand, the slope of lines decreases, and thus, the total energy decreases when $\theta$ increases. Figure 4 shows the thickness dependence of the in-plane $(M/M_0) \times L$, which implies the reduced thickness. It is obvious that the reduced thickness increases with increasing film thickness for all $\eta$ values.

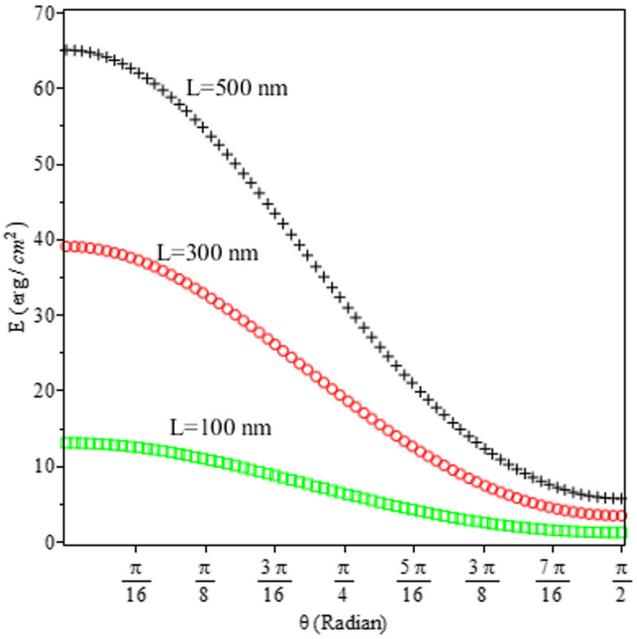


**Fig. 2** Value of the total energy as a function of the magnetization angle with different film thicknesses

However, the reduced thickness decreases with increasing $\eta$ values. Further, the curves shift right with increasing $\eta$ values. Therefore, we can confirm that the in-plane and out-of-plane magnetization behaviours are sensitive to the film thickness, dipolar length and perpendicular anisotropy constant.

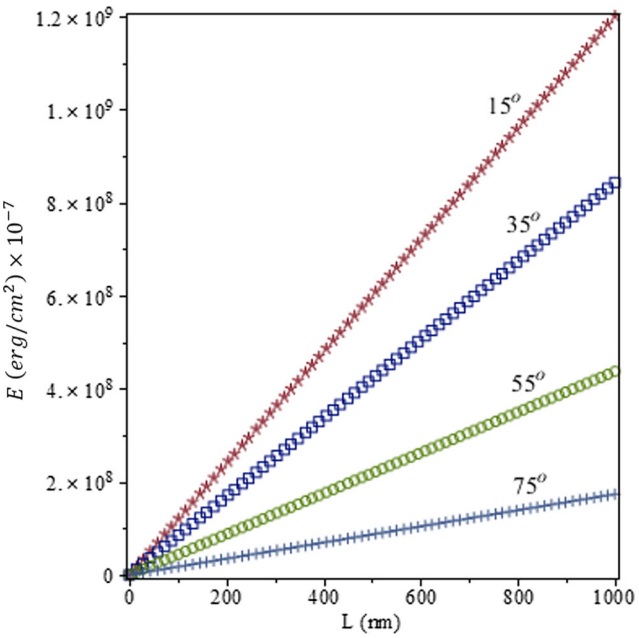


**Fig. 3** Thickness dependence of the total energy for various values of the magnetization angle

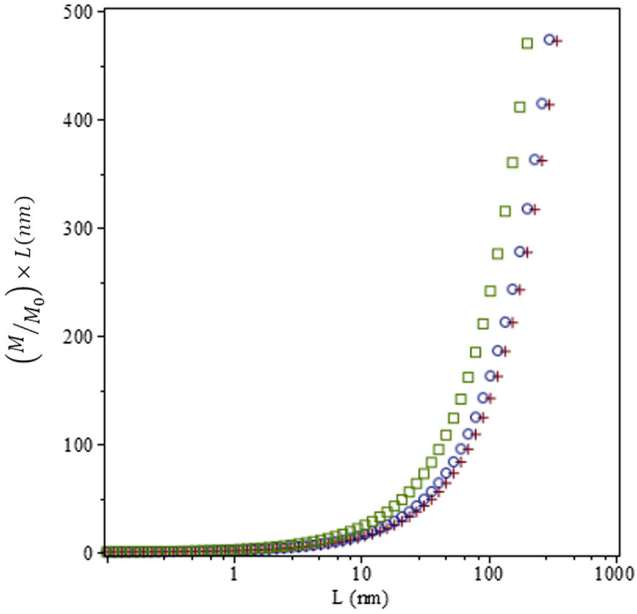


**Fig. 4** Thickness dependence of $[(M/M_0) \times L]$. (*square*: $\eta = 0.1$; *circle*: $\eta = 0.3$; *cross*: $\eta = 0.5$; $P_0/L = 10^{-3}$)

Although Ukleev et al. [2] and Engel-Herbert et al. [3] have observed the zigzag pattern in some of their thin films, they did not report any measured zigzag period vs dipolar length, the total energy vs the stable magnetization angle $\theta$ or film thickness $L$, and the in-plane reduced thickness vs film thickness. Therefore, we cannot perform a comparison between our zero field calculation and their experimental results. More recently, Pramanik et al. [16] have studied the magnetic anisotropy and magnetization reversal process in epitaxial chromium telluride thin films which possess strong magnetocrystalline anisotropy. They observed that the morphology of the surface shows the presence of features of different shapes (e.g. triangular) and sizes which can lead to magnetic domain structures in their thin film. The angular dependence of magnetization reversal in the film exhibits a complex nature. They have used $\eta = K_2/K_1 = 0.33$, which agrees well with our result. However, we will consider the modification to the theory of the in-plane and out-of-plane magnetization for the presence of magnetic field later.

In conclusion, the nature of zigzag walls is described in some detail together with the variation in the dipolar length. We calculated the total energy of the zigzag pattern in zero applied field considering uniaxial anisotropies. It is shown that the total energy depends on anisotropy constants, crystallographic orientation and film thickness for a given dipolar length. When the thickness of the films grows, the magnetostatic energy becomes important, inducing the magnetization to develop an in-plane component. The walls become wider, and it is interesting to remark the reduced film thickness, which contributes to the in-plane component of magnetization.

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