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Single-domain versus two-domain configuration in thin ferromagnetic prisms

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Abstract

Thin ferromagnetic elements in the form of rectangular prisms are theoretically investigated in order to study the transition from single-domain to two-domain state, with changing the in-plane aspect ratio p. We address two main questions: first, how general is the transition; second, how the critical value p_c depends on the physical parameters. We use two complementary methods: discrete-lattice calculations and a micromagnetic continuum approach. Ultrathin films do not appear to split in two domains. Instead, thicker films may undergo the above transition. We have used the continuum approach to analyze recent magnetic force microscopy observations in 30 nm-thick patterned permalloy elements, finding a good agreement for p_c.

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1. Introduction

In recent years, arrays of patterned ferromagnetic dots have received considerable interest owing to their possible applications in high-density magnetic data storage [1] and spin-electronic [2] devices, as well as for realizing logic functionality [3]. High-resolution electron beam lithographic techniques [4] are commonly used to fabricate the samples, in such a way that all the particles in the array are virtually identical to each other. As a consequence, the measured properties of the array can be interpreted as the individual properties of a single dot, provided that the dots are sufficiently far spaced to neglect the interdot magnetostatic interaction. In this way, using high-sensitivity magneto-optical magnetometry techniques, the variation of the properties with the shape in magnetic nanoelements could be experimentally investigated for dots as thin as 3 nm [5]. Single dot properties can also be investigated by magnetic force microscopy (MFM) techniques [6], which allow to focus on a single element.

In this paper, we will consider in-plane magnetized dots [1]. Within the plane, the preferred direction of the magnetization is determined by a balance between magnetic dipole–dipole interaction and magnetocrystalline anisotropy [7]. In Permalloy elongated nanodots, the direction of the uniform magnetization is determined by the shape-induced magnetic anisotropy, since the crystalline anisotropy of the material is negligible.

In a recent paper [8] we studied rectangular monolayers of planar spins located on the sites of a two-dimensional triangular lattice and interacting via magnetic dipole–dipole interaction only. For this lattice geometry, the infinite monolayer (ML) is believed [9] to have a ferromagnetic (FM) ground state, which is degenerate with the orientation. The infinite square lattice is instead believed to have a microvortex ground state, which is degenerate with a local orientation angle. For specific values of this angle, we get a state of FM lines antiferromagnetically coupled. Therefore, the difference between the two types of lattice is often understood in

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terms of the coupling between FM lines of spins, which is ferromagnetic in the triangular lattice and antiferromagnetic in the square lattice.

In our paper [8], rectangular monolayers were studied with varying their size and aspect ratio p, defined as the ratio between the smaller and the larger side of the rectangle.[1] Two main results came out. First, passing from rectangular, elongated finite systems to square-shaped ones, we obtained clear evidence for a transition from a FM to a two-domain and eventually to a macrovortex state configuration. Second, in the thermodynamic limit, we found that the macrovortex seems to be the lowest energy state whatever is the aspect ratio, but for elongated samples the size must attain unphysically large values to display such a state.

In this paper, we want to study the effect of a direct exchange interaction between spins, taking into account the effect of a variable thickness as well. These generalizations make our result relevant for FM prisms which are currently available. A recent paper [11] by Jubert and Allenspach moved along similar lines, with the authors studying the transition from single-domain to macrovortex configuration for a circular ferromagnetic disk. Here, we are rather interested in the problem of the transition from single-domain to two-domain configuration. For this reason, we study a thin rectangular ferromagnetic prism.

We want to address two main questions:

(i) How general is the transition? We have already shown [8] that this transition occurs for a purely dipolar system in the ML limit. Introducing the exchange coupling, A, makes the domain wall more energetically expensive and change the width of the domain wall: the latter is atomically sharp for a purely dipolar system, while it spreads over many lattice constants when $A \neq 0$. Here, we want to ascertain whether these changes are able to cancel the transition and whether lattice structure effects, which are so important for a purely dipolar system, are maintained.

(ii) If a transition occurs, how does the critical value, p_c, of the in-plane aspect ratio, p, of the rectangular element depend on the physical parameters of the system?

We will use two complementary methods for the evaluation of the magnetostatic energy difference, ΔE_M, between a two-domain state and a single-domain state: discrete-lattice calculations, which are valid for ultrathin films, and a micromagnetic continuum approach, applicable to thicker films.

In Section 2 discrete-lattice calculations are performed for a rectangular monolayer, both for spins located on a triangular and on a square lattice. Our main result is that the transition from a single-domain state to a two-domain state is suppressed, in the ultrathin limit, because of the exchange-induced broadening of the domain wall, which modifies the energetic balance of the dipolar energy. This result does not depend on the type of lattice, because spin configurations varying on scales much larger than the lattice constant depend weakly on lattice geometry.

In the case of thicker samples, a micromagnetic approach is appropriate. In Section 3 we calculate the magnetostatic energy difference, ΔE_M, between the two-domain and the single-domain state, following a method devised a few years ago by Aharoni [10]. In the limit of domain-wall width much smaller than the lateral dimensions of the ferromagnetic dot, analytical expressions can be obtained both for the magnetostatic energy gain, ΔE_M, due to *surface* charges and for the energy cost (per unit wall area), γ_N, of a one-dimensional Néel wall [12,13]. For a thin rectangular prism, γ_N includes contributions from the exchange interaction, the uniaxial magnetocrystalline anisotropy, and the magnetostatic energy due to *volume* charges in the Néel wall. One can thus estimate in a simple way the critical value, p_c, of the in-plane aspect ratio separating the single-domain phase from the two-domain phase.

An important remark is in order here. Introducing the exchange interaction, A, has a twofold effect: (i) the domain wall width is increased to a value $L_{dw} \approx \sqrt{A/K_1}$, where K_1 is the uniaxial anisotropy constant, and (ii) the domain wall energy density (i.e., the energy per unit wall area) is increased by a quantity of order $\sqrt{AK_1}$. A two-domain state can be energetically favorable if the gain in dipolar energy density coming from the two opposite domains, of order $M_s^2 b$ (where M_s is the saturation magnetization and $2b$ is the thickness), prevails on the full domain wall energy density, which has a dipolar contribution plus the just mentioned term of order $\sqrt{AK_1}$. A necessary condition for the transition to occur is that the two-domain configuration is energetically favorable when $A = 0$, because the exchange (and the anisotropy) only contribute to the cost of the energy balance, *not* to the gain. If the transition does occur when $A = 0$, one can wonder whether the transition is maintained when $A \neq 0$. One is thus led to conclude that, for comparable values of the anisotropy and dipolar energy densities ($K_1 \approx M_s^2$), the transition disappears because the domain wall energy density (of order $\sqrt{AK_1}$) surely dominates on the gain (of order $M_s^2 d$). Such a no-domain rule for in-plane configurations in ultrathin films had already been found in Refs. [7,14].

However, there are systems where K_1 is so small that the term $\sqrt{AK_1}$ is comparable to, or even smaller than, $M_s^2 b$: this is just the case of Permalloy. In fact, our theoretical predictions about the occurrence of a transition from a single-domain to a two-domain state in rectangular Permalloy dots when increasing the in-plane aspect ratio p are confirmed by recent MFM data [3] of *elliptic* patterned Permalloy elements with thickness 30 nm, lateral size 3 μm and p varying between the values $p = 0.13$ (elongated dot, single-domain state) and $p \lesssim 1$ (almost circular dot, two-domain state).

[1] Such a definition was adopted here for better convenience as regards the comparison with the experimental data in Ref. [3]. Note that it differs both from the one adopted by Aharoni in Ref. [10] and from the one we used in Ref. [8] ($r = 1/p$ rather than p).