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Magnetization process of the vortex state in soft magnetic thin square platelets

M. Wolf*, U.K. Rößler, R. Schäfer

IFW Dresden, P.O. Box 270116, D-01171 Dresden, Germany

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Abstract

An analysis of the magnetization process in magnetically ultra-soft thin film elements is presented for the case of square platelets, which show a vortex ground state and have a very low thickness. The analysis is based on micromagnetic calculations for systems with 1 μm edge length, 8–20 nm thickness and for material parameters similar to permalloy, but with negligible magnetic anisotropy. For the case of a field applied along the diagonal of the square platelet the evolution of magnetization, critical fields for the expulsion of the vortex and the leading energy terms have been determined from the numerical simulations. We show that a phase theory approximation, by using the position of the vortex as the only variable for the evolution of the vortex pattern, semi-quantitatively describes the main features of the reversible magnetization process and the stability limit. An effective demagnetization factor for the vortex pattern of the squares is determined from the numerical results. This effective parameter enables a quantitative description of the main properties of the vortex state and its magnetization process. Deviations of this phase-theory approximation from the numerical calculations are traced back to the evolution of inhomogeneous internal magnetization states, in particular wide walls that change their profiles under the applied field.

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1. Introduction

The behaviour of magnetically soft nanostructured samples is of large technical interest due to their potential and actual applications [1]. The magnetic patterns in such film elements are mainly determined by demagnetization effects that are governed by the geometry of the magnetized finite volume. For vanishing magnetic anisotropy, the magnetic microstructure in small thin film elements displays regular patterns with typical scales of the order of the sample dimension. The Néel-phase approximation [2] developed for bulk samples fails in this case because it presumes the existence of (i) domains with different magnetization directions due to magnetic anisotropy, (ii) domains that are separated by walls with negligible wall energy and (iii) ellipsoidal-shaped samples for which the demagnetization effect may be described by a demagnetization tensor. This description requires a well-defined hierarchy of lengths scales to hold between the macroscopic dimension of the sample, the typical domain size and the width of the domain walls. Generally, it is applicable for bulk anisotropic magnetic materials, but it is not expected to describe well micromagnetic patterns in thin films. However, mathematical theories based on scaling ideas for flux-closure structures [3–7] indicate that the regularity of these demagnetization patterns should allow the development of a deeper understanding and of relatively simple rules for their magnetization process in certain cases. Formulating such rules would enable to analyze the patterns and the magnetization process in finite soft-magnetic film elements, in particular for structures that are too large and complex for brute-force micromagnetic simulations.

*Corresponding author. Tel.: +49 351 4659 529.
E-mail address: m.wolf@ifw-dresden.de (M. Wolf).

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For zero applied field and vanishing anisotropy van den Berg [3,4] and Bryant and Suhl [5,6] analyzed the magnetization patterns in thin film elements, i.e. samples with a finite lateral dimension l and a vanishing thickness $t \to 0$. In this limit the demagnetization energy is dominating all the other energy terms and the magnetization distribution $\mathbf{J}(\mathbf{r})$ can be described by a two-dimensional field $\mathbf{m}'(x, y) = (m_x, m_y) = \mathbf{J}/J_s$ with the saturation magnetization J_s. This normalized magnetization $\mathbf{m}'$ obeys the equation $\partial_x m'_x(x, y) + \partial_y m'_y(x, y) = 0$, is restricted by the condition $|\mathbf{m}'| = 1$ and has a vanishing normal component on the boundary. These strong restrictions for a two-dimensional field cannot be fulfilled by a magnetization $\mathbf{m}'(x, y)$ continuous everywhere in the area. The loci of discontinuities, i.e. singularities of $\mathbf{m}'(x, y)$ form the walls. The whole reasoning does not depend on the existence of any crystalline magnetic anisotropy. Thus, for $t \to 0$ walls of this type must occur also for vanishing anisotropy. Hence, these walls are very different from classic Bloch/Néel walls in usual anisotropic magnets, although the internal structure of the walls may be akin to these wall types. The methods as developed by these authors to construct domain patterns and the position of such walls allow for a variety of patterns in soft thin film elements. As the demagnetization energy enters here only to derive the constraints on $\mathbf{m}'(x, y)$, one cannot decide which of the permitted domain patterns has the lowest energy.

In principle, the quasistatic magnetic behaviour of thin film elements follows by minimising the usual micromagnetic energy

$$E_{\text{tot}}(\mathbf{m}) = A \int d^3r |\nabla \mathbf{m}|^2 + \frac{\mu_0}{2} \int d^3r\, \mathbf{H}^2_{\text{dem}} - J_s \int d^3r\, \mathbf{m}(\mathbf{r})\, \mathbf{H}_{\text{ext}}(\mathbf{r}), \tag{1}$$

with appropriate boundary conditions [8,9]. The first term of Eq. (1) describes the exchange interaction, the second is the magnetostatic interaction or demagnetization energy and the last one is the energy of the magnetization distribution $J_s\mathbf{m}(\mathbf{r})$ in an applied field $\mathbf{H}_{\text{ext}}$. Here J_s is the saturation magnetization and $\mathbf{m}(\mathbf{r})$ is subject to the constraint $|\mathbf{m}| = 1$. In Eq. (1) magnetic anisotropy energy has been omitted, as we are interested in ultra-soft magnetic materials. Obviously, the first term favours a homogeneous $\mathbf{m}(\mathbf{r})$, whereas the second one prefers patterns with flux closure. Minimization of the energy (1) allows for a variety of patterns as well as for different types of magnetization behaviour and hysteresis, because (i) the solution depends on the magnetic field history and/or the specific boundary conditions, (ii) besides the geometrical scales thickness t and lateral dimension l of the sample, the energy E_{tot} itself sets a characteristic scale, the so-called exchange length d, given by $d^2 = 2A\mu_0/J_s^2$. Thus, generally, various different local minima of problem (1) are visited when the external field $\mathbf{H}_{\text{ext}}$ is changed. DeSimone et al. [7,10] presented in a number of publications a detailed scaling analysis of the different energy contributions embodied in the micromagnetic functional, Eq. (1), in the limit of vanishing thickness $t \to 0$. These considerations allow important conclusions on the relevance of the different energy contributions for the magnetization behaviour. Moreover, the scaling results suggest that external fields are expelled over wide areas of the film elements. This analysis shows that the internal field and the magnetization structures can follow rather simple rules below certain thresholds for the applied magnetic field, in particular, the internal field can remain homogeneous within wide fractions of the film area. Experimental studies with this background have been presented in Refs. [11–13].

The scaling analysis by DeSimone et al. generalizes the previous constructions of flux-closure structures for ultra-soft thin film elements in the limit of two-dimensional magnetization distributions as discussed by van den Berg [3,4] and Bryant and Suhl [5,6] for the case of zero and weak external fields. DeSimone et al. [11,12] discuss also the case of sizeable external fields, when the flux-closure breaks down and the external field penetrates into certain regions of the magnetized film. It is important to note here that this field penetration takes place above a certain threshold field. Below this threshold, for $t \to 0$, the internal field remains zero and homogeneous.

According to this analysis, smaller energy contributions are related to the inhomogenously distorted magnetization near walls, etc. These terms, however, are significant for the choice between different competing realizations of flux-closure structures and for the hysteretic magnetization processes. The formation and details of the wall structures depend on the film thickness. It has to be emphasized that the powerful mathematical scaling ideas give rigorously valid results and bounds only in the limit of vanishing thickness, $t \to 0$. The magnetic behaviour of films with finite thickness may display certain deviations from this idealized behaviour and the relevance of the mathematically rigorous limit for samples of finite thicknesses is not obvious. Therefore, it is interesting to analyze the behaviour of magnetic microstructures from numerically "exact" solutions for film elements with finite thickness and larger lateral dimensions for cases in which such calculations are still viable.

As the simplest pattern, we have chosen here the vortex state in a square platelet with an applied field along the diagonal of the square. This pattern is already highly complex and displays main features like walls and a vortex that are also found in more extended magnetization patterns (see, e.g., Refs. [14,15]). Nevertheless, it turns out that the pattern and the magnetization process remain rather simple for our model system. Based on an analysis of the exact numerical solutions, we find that the evolution of magnetization pattern can be described by a simple effective theory, which describes the evolution of the vortex state by the vortex position instead of the full magnetization distribution. This theory requires only the vortex position as a single variable and an effective