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Micromagnetic calculation of the thickness dependence of surface and interior width of asymmetrical Bloch walls[1]

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Abstract

The wall width of asymmetrical Bloch walls was calculated numerically over a wide thickness range. Careful extrapolation was used to eliminate numerical finite size effects. On the surface a larger wall width as in the interior was expected and found due to the asymmetrical character of the wall. However, no saturation of the surface wall width with increasing thickness was observed. Instead we found a power law for the surface wall width δ_w as a function of the reduced thickness D of the form $\delta_w \propto D^{0.14}$ within the investigated thickness range. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The transition of the internal structure of domain walls from vortex-like asymmetrical Bloch walls in thick films [1,2] to nearly one-dimensional classical Landau-type walls in bulk samples has been studied for many years [3–6]. Independent of the thickness of a sample, Bloch walls produce surface vortices to avoid stray fields. The details of the surface vortices and their width has not been studied systematically, however. Since they are of interest in connection with experimental observations we applied a numerical micromagnetic procedure in two dimensions to investigate this problem again. We focus on uniaxial materials with in-plane anisotropy (Fig. 1). The calculations were extended up to a thickness of 160 times the Bloch wall width parameter $\sqrt{A/K_u}$ (A = exchange constant, K_u = uniaxial anisotropy constant). In the following all lengths are expressed as multiples of this length scale.

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2. Wall structure development for $Q = 0.1$ with increasing thickness

The material was characterized by the reduced quantity $Q = K_u/K_d$ ($K_d = J_s^2/2\mu_0$). A value of $Q = 0.1$ was chosen. This relatively large value of the anisotropy is well within the stability range of the asymmetrical Bloch walls [7] and is favourable for efficient micromagnetic computations. In addition, a Q-value close to unity avoids large differences between the two characteristic micromagnetic lengths $\sqrt{A/K_u}$ and $\sqrt{A/K_d}$ (due to the relation $\sqrt{A/K_d} = \sqrt{Q}\sqrt{A/K_u}$). This guarantees that even fine details of the micromagnetic configuration near the surfaces (where the magnetization pattern has to fulfill the micromagnetic boundary condition $\partial m/\partial n = 0$) were correctly described by the discretization. Because the thickness of this surface layer scales with $\sqrt{A/K_d}$ (see Ref. [1]) the discretization requirements for its proper representation would be much more demanding for very soft materials such as Permalloy ($Q = 2.5 \times 10^{-4}$).

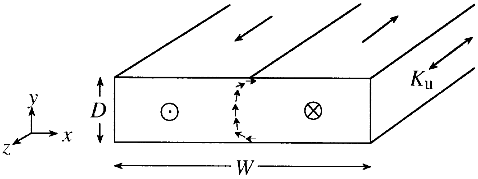

Fig. 1. Geometry of the wall calculation.

For $Q = 0.1$ we were able to manage a thickness of $D = 160\sqrt{A/K_u}$ by using 1024 cells in the thickness dimension which correspond to about 2 cells per exchange length $\sqrt{A/K_d}$. For typical values of $J_s = 1\ T$ and $A = 10^{-11}$ J/m this maximum thickness amounts to a film thickness of 8 μm. The exchange length $\sqrt{A/K_d}$ and the wall width parameter $\sqrt{A/K_u}$ become 16 and 50 nm for these parameters, respectively.

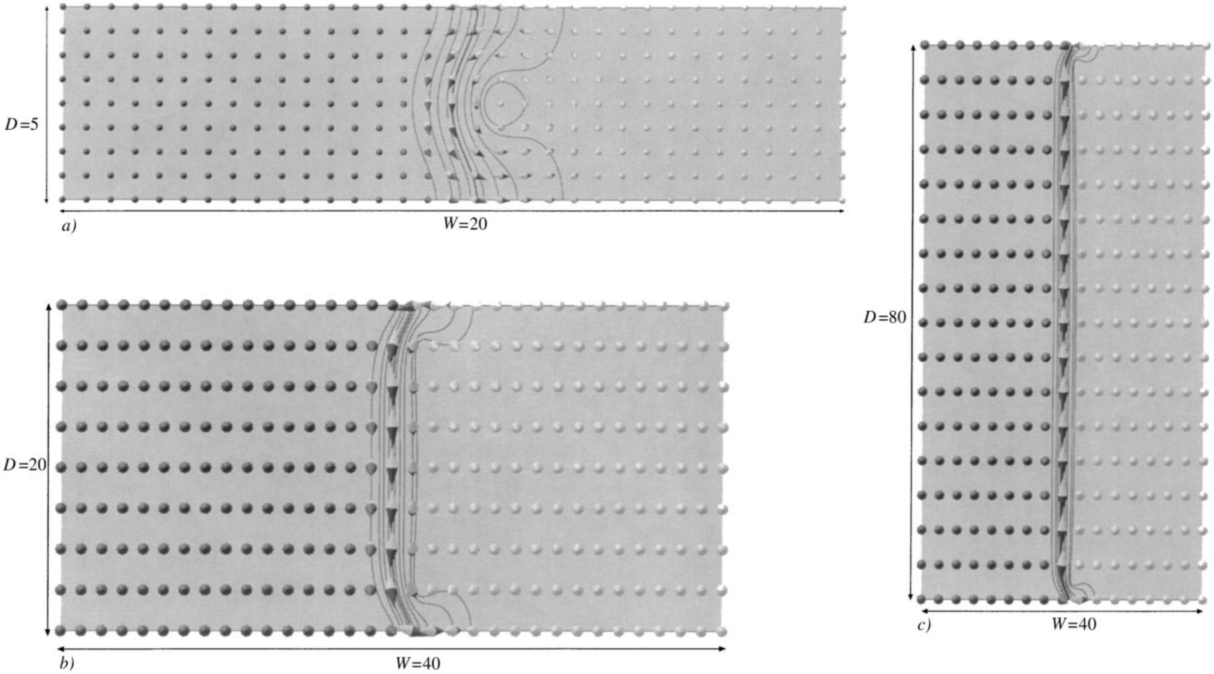

Fig. 2. Wall structures for increasing sample thickness: the vortex at $D = 5$ (a) gets successively separated into two semi surface vortices (b,c). In addition to the magnetization represented by the double cones contour lines at $\gamma = -0.9, -0.7, -0.5, -0.2, 0, 0.2, 0.5, 0.7, 0.9$ and 0.95 are shown. The core line $\gamma = 0$ where the magnetization rotates through the xy-plane is indicated by a thicker line.

The wall structures were calculated by minimizing the sum of exchange, anisotropy and stray field energy contributions. Details of the numerical method can be found in Refs. [8,7]. As an additional check the wall energy was evaluated in two different ways as suggested by Aharoni [9]. The difference was always less than 0.1%, thus confirming the self-consistency of our results.

Examples of the calculated walls are shown in Fig. 2. Here the development of the asymmetrical Bloch wall structures with increasing thickness is exemplified for $D = 5$, 20 and 80 using double cones for the magnetization direction and contour lines for the m_z- or γ-component. The isometric vortex at $D = 5$ (Fig. 2a) gets more and more split into two semi-vortices close to the surfaces for $D = 20$ and $D = 80$ (Fig. 2b and c). Thereby a larger and larger section in the interior develops the character of a purely one-dimensional Bloch wall.

The surface structure of the wall for the thickness of $D = 160$ is displayed in Fig. 3 with two magnifications of the surface zone. Fig. 3b visualizes, that Bloch walls are terminated by a one-sided, stray-field free *cap* at the surface.

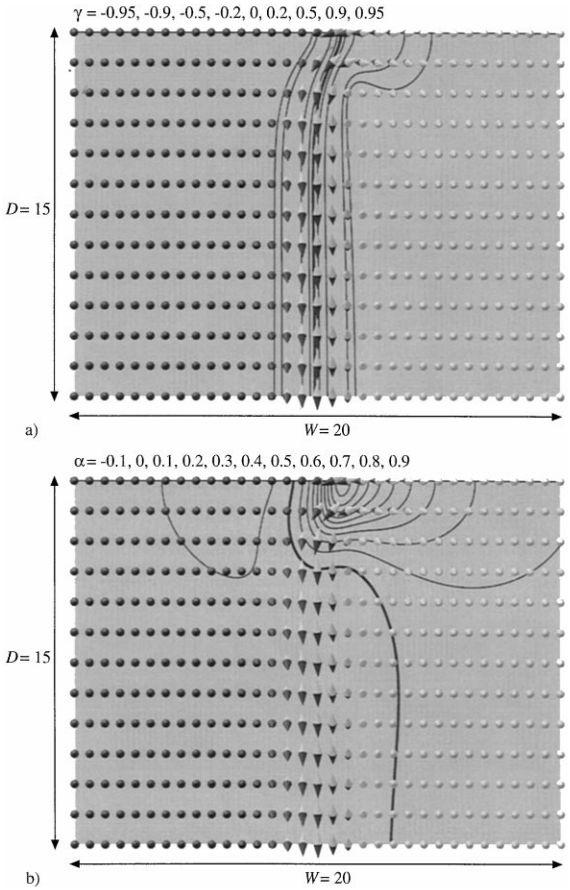

Fig. 3. The surface wall structure at $D = 160$: Contours of constant γ (a) and α (b) are shown in two blow-ups of 20×15 length units. The choice of a relatively large Q allows at least two points on the exchange length in the surface layer.

3. Extrapolation to results for an infinite plate

Typical magnetization profiles for the mid-plane as well as for the surface are shown in Fig. 4. These profiles were used to evaluate appropriate values of the wall widths. For the inner wall width two definitions based on the tangent of the component m_z and on the integral over the component m_y were used. On the surface the integral of m_x (between its zeros or integrated to 0 or W in the case no zero was found) was evaluated (due to the strong asymmetry of the $m_x(x)$-profile a tangent definition would give misleading values in this case).

While experiments are usually done on extended films or plates, all calculations were performed for relatively narrow strips of width W as in [7]. The walls were first calculated with successively refined periodic grids. Then wall widths for an infinitely fine grid were derived from these data by extrapolation to zero cell size as shown for two examples in Fig. 5.

In a second step the calculations for a given thickness D were performed as a function of the strip width W. Results are shown in Fig. 6 for the two integral wall widths. All values in this diagram have already been extrapolated to an infinitely fine grid. With increasing strip width (decreasing aspect ratio D/W) the wall width approaches a constant value which is taken to be representative of the infinitely extended plate.

The different wall widths thus obtained are plotted as a function of reduced thickness in Fig. 7. Most remarkable is the fact that the integral surface wall width does not appear to saturate. While the interior wall widths approach their classical values

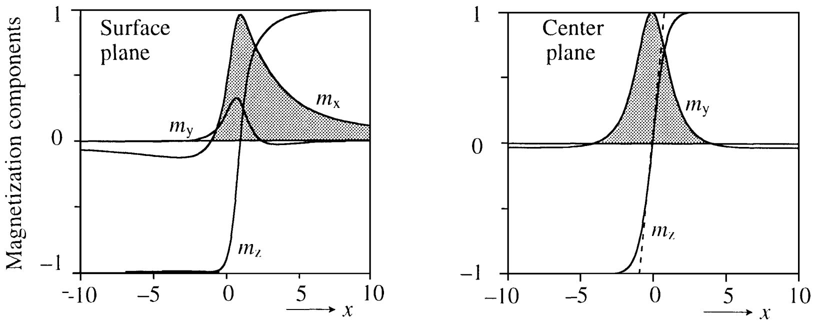

Fig. 4. Typical magnetization profiles in the center plane and at the surface used for the evaluation of wall width parameters. The curves are taken from calculations for the combination $D = 40$ and $W = 80$. The shaded areas were evaluated for the integral wall widths.

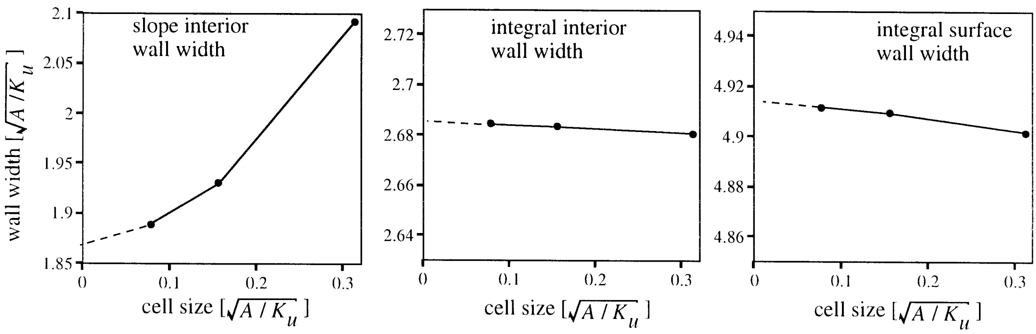

Fig. 5. Extrapolation of the wall width to zero cell size for three different wall widths. The data were taken for the combination $D = 40$ and $W = 80$.

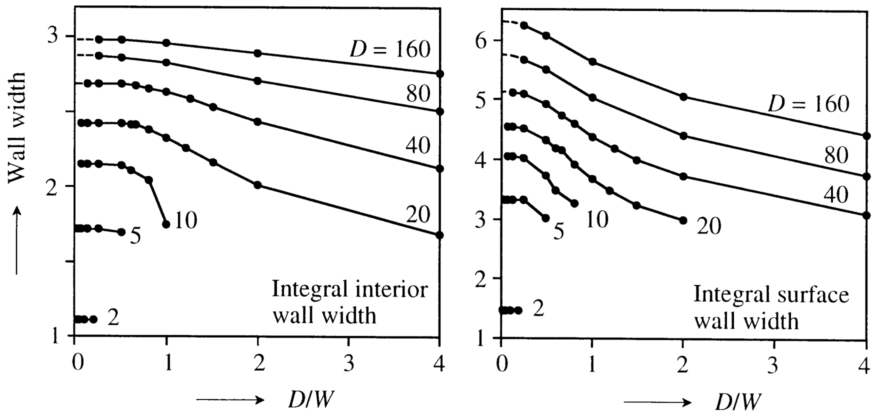

Fig. 6. Integral interior and surface wall width as a function of the aspect ratio D/W of the calculation strip (see Fig. 1) demonstrating the extrapolation to infinitely wide plates.

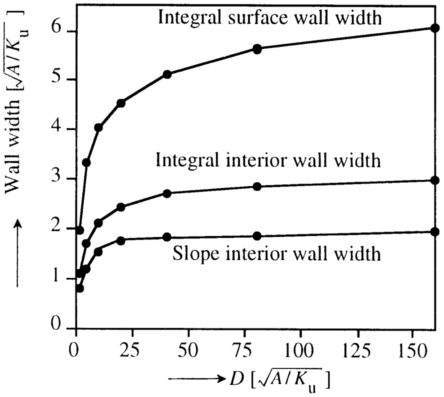

Fig. 7. The different wall widths as a function of the reduced thickness D.

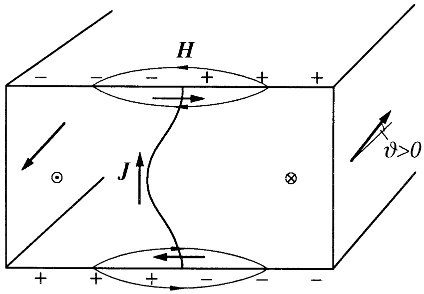

Fig. 8. Effect of a slight tilt of the easy axis: the generated surface charges in the domains disfavour the surface magnetization of the wall for a positive angle ϑ.

2 and π asymptotically, a steady increase of the surface wall width is observed within the investigated thickness range. It can be described by a power law proportional to $D^{0.14}$. This phenomenon is probably due to the fact that the surface vortex can reduce its exchange energy by expanding its outer part with increasing thickness into a larger and larger area.

4. Consequences for experimental wall observations

According to our calculations the extended surface tails of Bloch walls in bulk material appear to be a "soft" feature. They are strongly modified by secondary influences as can be seen from numerical experiments. For example, we tested the case in which the easy axis is slightly misoriented (tilted relative to the surface). For a thickness of $D = 40$ for which the integral interior wall width amounts to $W_0 = 2.7$ (independent of misorientation), the integral surface wall width decreases from 4.91 to 4.33 for $+2^\circ$ misorientation, and increases to 5.42 for -2° misorientation (all lengths in units of $\sqrt{A/K_u}$). For positive misorientation ϑ the stray fields generated by the domain surface charges disfavour the magnetization in the surface part of the vortex for the chosen wall orientation as depicted in Fig. 8.

In another experiment, the anisotropy parameter Q was reduced to 0.025. While the interior wall width W_0 remained again unaffected for $D = 40$, the surface wall width increased from 4.91 to 5.53 in this case. Experimental observations of the surface wall width should therefore not be considered suitable for the determination of fundamental material parameters such as the exchange stiffness constant A.

Acknowledgements

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