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Head-to-head domain wall structures in wide permalloy strips

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We analyze the equilibrium micromagnetic domain wall structures encountered in Permalloy strips of a wide range of thicknesses and widths, with strip widths up to several micrometers. By performing an extensive set of micromagnetic simulations, we show that the equilibrium phase diagram of the domain wall structures exhibits in addition to the previously found structures (symmetric and asymmetric transverse walls, vortex wall) also double vortex and triple vortex domain walls for large enough strip widths and thicknesses. Also several metastable domain wall structures are found for wide and/or thick strips. We discuss the details of the relaxation process from random magnetization initial states towards the stable domain wall structure and show that our results are robust with respect to changes of, e.g., the magnitude of the Gilbert damping constant and details of the initial conditions.

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I. INTRODUCTION

During the last decade, a lot of effort has been devoted to understanding static and dynamic properties of magnetic domain walls (DWs) in ferromagnetic nanostructures such as nanowires and nanostrips. These studies have been largely driven by promising technological applications based on domain walls and their dynamics, in particular memory [1,2] and logic devices [3–5]. In typical experiments DWs are driven by either applied magnetic fields [6,7] or spin-polarized electric currents [8–11]. The resulting DW dynamics depends crucially on the micromagnetic DW structure, typically involving various internal degrees of freedom. These are essential, e.g., for the emergence of the Walker breakdown [12], an instability occurring when the DW internal degrees of freedom get excited by a strong external drive (a magnetic field \(H\) or a spin-polarized current \(J\) exceeding the Walker field \(H_W\) or current \(J_W\), respectively), limiting the propagation velocity of the DWs.

Two main classes of ferromagnetic materials have been extensively studied within the strip geometry. Materials with a high perpendicular magnetic anisotropy (PMA [13–16]) exhibit simple and narrow DWs of the Bloch and/or Néel type. For \(H > H_W\) or \(J > J_W\), repeated transitions between these two structures are observed [16]. The second class of systems includes soft (low anisotropy) magnetic materials [13,14] such as Permalloy, where in-plane domain magnetization along the long axis of the strip is induced by shape anisotropy. By using various experimental techniques [17,18] and micromagnetic simulations, it has been established that the equilibrium DW structures separating these in-plane domains are more complex and depend crucially on the sample geometry [19–22]. Transverse DWs (TWs) and asymmetric transverse DWs (ATWs) are observed for narrow and thin strips [22–27], while in wider and thicker strips one encounters the vortex DW (VW) [22,24–26,28,29]. In addition, various metastable DW structures with higher energy may be found [18,28–31]. For \(H > H_W\) or \(J > J_W\), the DW structures exhibit dynamical evolution: For TWs, repeated nucleation and propagation of an antivortex across the strip width takes place [19]. Similarly, in VWs the vortex core performs oscillatory back and forth perpendicular motion [19].

In Permalloy strips with even larger widths and/or thicknesses, one might expect also other, possibly more complicated, equilibrium DW structures. For wider strips shape anisotropy is less important, implying that energy minima with more complex spin structures closing the flux more efficiently than TWs, ATWs, or VWs may appear. Indeed, e.g., double and triple vortex DWs have been observed in experiments on wide strips [28], but they have been attributed to current-induced vortex nucleation resulting in metastable DW structures. Consequently, a pertinent and fundamental question is: What are the possible intermediate equilibrium DW structures observable when the lateral Permalloy strip dimensions increase from those corresponding to the typical nanostrip geometry (with TW, ATW, or VW as the stable DW structure) to strip widths of micrometers and beyond.

In this paper we present an extensive numerical study of the equilibrium and metastable micromagnetic DW structures in Permalloy strips, with the strip widths up to an order of magnitude larger than before [19–24]. Contrary to previous studies focusing on comparing the energies of different \(a\ priori\) known DW structures [19–24], we perform micromagnetic simulations of relaxation dynamics from random initial states towards the stable DW structures. In addition to the previously observed TW, ATW, and VW DWs, we find also DWs with equilibrium double and triple vortex structures for wide and/or thick enough strips. The last structure is encountered only in the very largest system sizes we were able to simulate. Moreover, for wide strips we find a rich variety of metastable DWs with even more complex micromagnetic structures. We demonstrate that our results are robust with respect to changes of the magnitude of the Gilbert damping constant or using different initial conditions for the relaxation process. Our results underline the crucial role of topological defects for physics of DWs in soft strips, and that of micromagnetic simulations for finding the true equilibrium DW structure.

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been included. Between them, a region of random magnetization (of length \( l_r \)) has been included.

**II. MICROMAGNETIC SIMULATIONS**

The system studied is a Permalloy strip of width \( w \) and thickness \( \Delta_z \), satisfying \( \Delta_z \ll w \), see Fig. 1 (a). In the micromagnetic simulations, magnetic charges are compensated on the left and right ends of the strip, to mimic an infinitely long strip; the actual simulated length satisfies \( l \geq 4w \) for all cases considered. The initial state from which the relaxation towards a stable DW structure starts is an in-plane head-to-head domain structure, with a region of random magnetization of length \( l_r \) in the middle of the sample, see Fig. 1(b). If not specified otherwise, we consider \( l_r = 2w \).

Material parameters of Permalloy are used, i.e., saturation magnetization \( M_s = 860 \times 10^3 \) \( \text{A/m} \) and exchange constant \( A_{ex} = 13 \times 10^{-12} \text{J/m} \). The typical Gilbert damping constant for Permalloy is \( \alpha = 0.01 \), but here we analyze also the influence of \( \alpha \) on the relaxation process and thus consider also other values. For simplicity, we set the temperature \( T \) to zero and focus on the ideal case of strips free of any structural disorder or impurities.

The simulations are performed using the GPU-accelerated micromagnetic code MuMax3 \([32–34]\), offering a significant speedup as compared to CPU codes for the large system sizes we consider here. To calculate the magnetization dynamics of the system, the Landau-Lifshitz-Gilbert equation \([35,36]\),

\[
\frac{\partial \mathbf{m}}{\partial t} = \gamma \mathbf{H}_{\text{eff}} \times \mathbf{m} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t},
\]

is solved numerically. Here, \( \mathbf{m} \) is the magnetization, \( \gamma \) the gyromagnetic ratio, and \( \mathbf{H}_{\text{eff}} \) the effective field, with contributions due to exchange, Zeeman, and demagnetizing energies. The size of the discretization cell used depends on the system size, but is always bounded by the exchange length, \( \Lambda = (2A/\mu_0 M_s^2)^{1/2} \approx 5 \text{ nm} \), in the in-plane directions, and equals \( \Delta_z \) in the out-of-plane direction.

**III. RESULTS**

We start by considering the effect of varying \( \alpha \) and \( l_r \) on the relaxation process. Figure 2 shows an example of the time evolution of \( \mathbf{m}(r,t) \) for \( w = 420 \text{ nm} \), \( \Delta_z = 10 \text{ nm} \), \( \alpha = 3 \), and \( l_r = 2w \). The initially random magnetization evolves via coarsening of the defect structure of the magnetization texture towards the stable DW (here, a VW). During the relaxation, the total energy \( E \) of the system decreases in a manner that for a given geometry \( (w \) and \( \Delta_z) \) depends on both \( \alpha \) and \( l_r \), see Figs. 3(a) and 3(b) where \( w = 5120 \text{ nm} \) and \( \Delta_z = 20 \text{ nm} \) is considered. For instance, \( E \) decreases faster for an intermediate \( \alpha \) [Fig. 3(a)]. We attribute this behavior to the

\[
\frac{E(t) - E(t)}{t} \propto \beta \text{ for } t \approx 1.3.
\]

For the \( \alpha = 0.3 \) case shown here, \( \beta \approx 1.3 \). Empty (filled) symbols in (c) correspond to \( w = 420 \text{, } \Delta_z = 10 \text{ nm} \) (\( w = 860 \text{, } \Delta_z = 20 \text{ nm} \)).

\[
\begin{align*}
\text{(a)} & \quad \alpha = 3 \\
\text{(b)} & \quad \alpha = 0.3 \\
\text{(c)} & \quad \alpha = 0.3
\end{align*}
\]

FIG. 2. (Color online) An example of the temporal evolution of the relaxation, with \( w = 420 \text{ nm} \), \( \Delta_z = 10 \text{ nm} \), \( \alpha = 3 \), and \( l_r = 2w \). Relaxation towards the equilibrium DW structure (here, a VW) takes place via coarsening dynamics of the defect structure in the magnetic texture. The color wheel in the middle shows the mapping between magnetization directions and colors.

FIG. 3. (Color online) The energy \( E(t) \) as a function of time \( t \) for \( w = 5120 \text{ nm} \) and \( \Delta_z = 20 \text{ nm} \). (a) For different values of \( \alpha \) and \( l_r = 2w \). (b) For different values of \( l_r \), and \( \alpha = 0.3 \) [resulting in the fastest relaxation in (a)]. (c) shows that on average, the early time decay of \( E(t) \) towards its final value \( E_f \) obeys \( \langle E(t) - E_f \rangle \propto t^{-\beta} \). For the \( \alpha = 0.3 \) case shown here, \( \beta \approx 1.3 \). Empty (filled) symbols in (c) correspond to \( w = 420 \text{, } \Delta_z = 10 \text{ nm} \) (\( w = 860 \text{, } \Delta_z = 20 \text{ nm} \)).
balance between inertial effects related to precession favored by a small $\alpha$, helping to overcome energy barriers, and the higher rate of energy dissipation due to a large $\alpha$. Thus, the relaxation time to reach a (meta)stable DW structure depends on $\alpha$. Figure 3(b) illustrates that for a fixed $\alpha$, systems with a larger $l_1$ relax more slowly. Figure 3(c) shows that on average, the early-time relaxation of $E$ towards its final value $E_\text{f}$ exhibits temporal power-law decay, $(E - E_\text{f}) \propto t^{-\beta}$ with $\beta \approx 1.3$ for the $\alpha = 0.3$ case shown, possibly related to collective effects due to interactions between several topological defects during early stages of relaxation (Fig. 2).

In general, the final (meta)stable DW structure may depend on the realization of the random initial state. Thus, we consider 21 realizations of the initial random magnetization for each $w$ and $\Delta_z$ and compare the energies of the resulting relaxed configurations. The structure with the lowest energy is chosen as the equilibrium structure, while others with higher energy are metastable states. Although, as discussed above, the relaxation times depend on $\alpha$ and $l_1$, the equilibrium DW structure is found to be independent of $\alpha$ and $l_1$ in the range considered, i.e., $\alpha \in [0.01, 3]$ and $l_1 \in [w, 3w]$. Thus, in what follows, we will use $\alpha = 3$ and $l_1 = 2w$.

The main results of this paper are summarized in Figs. 4 and 5, showing the phase diagram of the equilibrium DW structures for $w$ ranging from 120 to 5120 nm, and $\Delta_z$ from 5 to 25 nm, and examples of these structures, respectively. For small $w$, we recover the previous results [19–22], i.e., phases corresponding to TW, ATW, and VW, shown in Figs. 5(a), 5(b), and 5(c), respectively.

For larger strip widths ($w$ approaching or exceeding 1 $\mu$m, depending on $\Delta_z$, see Fig. 4), a new equilibrium micromagnetic DW structure, a double vortex wall (DVW), is observed. This structure consists of two vortices with an opposite sense of rotation of the magnetization around the vortex core, see Fig. 5(d). At the phase boundary (blue triangle symbols pointing left in Fig. 4), VW and DVW have the same energy. The DVW phase spans a relatively large area within the $(w, \Delta_z)$ space, highlighting the robustness of our results.

In addition, a second new phase, with a triple-vortex wall (TVW) as the equilibrium structure [see Fig. 5(e)], is found for the very largest system sizes we have been able to simulate. The middle vortex of the TVW has an opposite sense of rotation to the other two. For $w = 5120$ and $\Delta_z = 25$ nm, DVW and TVW have the same energy (the cyan square symbol in the top right corner of Fig. 4), suggesting the presence of a phase boundary between the two structures. Indeed, by performing a set of 10 additional simulations with $w = 6144$ and $\Delta_z = 25$ nm (i.e., outside the phase diagram in Fig. 4), it is evident that TVW is the equilibrium DW structure for very large strip widths. This structure has been observed in experiments as a metastable state for smaller systems [28,29]. Notice also that the middle part of the TVW [Fig. 5(e)], exhibiting four line-like 90° DWs meeting at a vortex core in the middle of the TVW, resembles the typical Landau flux-closure magnetization patterns observed for rectangular Permalloy thin films [37–39].

Following the relaxation from a random magnetization initial state, the system may in general end up into various metastable states with higher energy than that of the equilibrium DW. Sometimes these metastable states have even a higher probability than the equilibrium one, estimated here from the sample of 21 relaxed configurations. Figure 6 shows some of the metastable states found for a large strip with $w = 5120$ nm and different values of $\Delta_z$; for strips with smaller lateral dimensions, different metastable states tend to be less numerous and have a simpler structure. Despite their apparent complexity, all the metastable DW structures shown in Fig. 6 respect the basic principles of topology of DWs. Each of the DWs is composed of topological defects,
and the metastable states in Fig. 6 obey the principle of compensation of topological defects to yield a total winding number of zero. The richness of the equilibrium phase diagram and the large collection of metastable states indicate that for wide/thick strips in particular, the micromagnetic energy landscape is quite complex, with a large number of local minima. This is also in agreement with our observations of power-law energy relaxation.

**IV. SUMMARY AND CONCLUSIONS**

To summarize, we have performed an extensive set of micromagnetic simulations to study the equilibrium and metastable DW structures in Permalloy strips of a wide range of widths and thicknesses, as well as the relaxation dynamics starting from random magnetization initial states. The general trend of our results is that both the equilibrium and metastable DW configurations become increasingly complex (i.e., they consist of an increasing number of topological defects) as the lateral strip dimensions increase. We note that somewhat analogous behavior—i.e., existence of equilibrium magnetization configurations with increasing complexity as the system size increases—is observed also in some other systems such as three-dimensional cylindrical elements with perpendicular anisotropy [41,42].

Several remarks are in order: First, for strips with even larger lateral dimensions one may in principle expect more complex DW patterns, possibly with four or more vortices with an alternating sense of rotation. These, however, are currently beyond the reach of our available computing resources. Second, our phase diagram allows one to check if experimental observations of the various DW structures in wider strips are equilibrium configurations or metastable states. According to our review of the experimental literature, most observations of DVWs and TVWs appear to be metastable states [28,29].

Third, while the equilibrium structures we find are certainly stable in the absence of external perturbations such as applied magnetic fields, it remains to be seen what their field driven dynamics is like, and whether wide strips with a relatively weak shape anisotropy are able to support the DWs as compact objects also when external perturbations are being applied [43].

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