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Metastable magnetic domain walls in cylindrical nanowires

C.A. Ferguson, D.A. MacLaren, S. McVitie *

SUPA, School of Physics & Astronomy, The University of Glasgow, Glasgow G12 8QQ, United Kingdom

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ABSTRACT

The stability of the asymmetric domain wall (ATDW) in soft magnetic cylindrical nanowires and nanotubes is investigated using micromagnetic simulations. Our calculated phase diagram shows that for cylindrical permalloy nanowires, the transverse domain wall (TDW) is the ground state for radii below 20 nm whilst the Bloch point wall (BPW) is favoured in thicker wires. The ATDW stabilises only as a metastable state but with energy close to that of the BPW. Characterisation of the DW spin structures reveals that the ATDW has a vortex-like surface spin state, in contrast to the divergent surface spins of the TDW. This results in lowering of surface charge above the critical radius. For both cylindrical nanotubes and nanowires we find that ATDWs only appear to exist as metastable static states and are particularly suppressed in nanotubes due to an increase in magnetostatic energy.
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1. Introduction

Much research into domain walls (DWs) in magnetic nanowires has focused on flat, planar DW guides that have potential spintronic applications including racetrack memory [1], shift registers [2] and domain wall logic devices [3]. In these two dimensional (2-D) systems, and in the absence of strong magnetocrystalline anisotropy, the magnetisation is restricted to lie in-plane, pointing along the wire axis to form head-to-head or tail-to-tail Néel DWs. The spin microstructure of the DW itself then depends on the nanowire dimensions, as summarised by phase diagrams [4, 5] that in the case of soft magnetic materials such as permalloy (Py) identify three principal DW types. For wide, thick wires, the high magnetostatic energy associated with an abrupt head-to-head wall can be reduced by the inclusion of a vortex state. However, there is a minimum vortex diameter set by exchange energy so that reduction of the wire width below this value leads to a first-order [5] phase change and the production of a transverse DW. This second DW type has a triangular region of magnetisation lying perpendicular to the wire axis and its formation can be mediated by the third DW type, an asymmetric transverse DW, which has both a triangular form and retains some of the curling magnetisation of the vortex state but lacks a vortex core. Both the DW structure and its chirality are important for applications since they have been shown to influence the DW pinning potential [6]. In addition, a number of studies have shown the importance of metastable states, particularly in dynamic systems, where the DW is shifted using a spin-polarised current or applied magnetic field. Experiments have shown that DWs can change type during propagation along the guide. Indeed, propagation of DWs in planar nanowires is ultimately limited by Walker breakdown, [7] which describes a process whereby an anti-vortex structure is periodically nucleated and annihilated at the wire edges [8], causing the motion of the DW to become non-uniform. A full understanding of both ground state and metastable (or transient) DW structures is therefore essential for device design.

In contrast to planar guides, the three dimensional (3-D) nature of cylindrical nanowires (CNWs) and cylindrical nanotubes (CNTs) has attracted interest because simulations and numerical models have predicted it to suppress Walker breakdown [9,10] in favourable cases. These 3-D structures lack lateral edges, thus preventing the nucleation of individual anti-vortex states and leading to the prediction that Walker breakdown by the nucleation of a single anti-vortex is topologically forbidden [11]. In other respects, many phenomena of 2-D nanowires have analogues in the 3-D case. Studies of magnetisation reversal in soft magnetic CNWs reveal that two distinct DWs are stable [12,13] –a transverse domain wall (TDW) and a Bloch point wall (BPW) and are related to the 2-D transverse and vortex states, respectively. The situation is similar for CNTs, except that a Bloch point need not form in the absence of a magnetic core along the CNT axis, producing instead a vortex DW (VDW) that has a similar external spin structure to the BPW [12]. Phase diagrams again show that the TDW is the ground state for thinner wires; the BPW/VDW for thicker wires. One might therefore expect the analogy with 2-D structures to continue and so predict the existence of a third DW structure; and a recent electron holography study [14] identified the existence of a such a

* Corresponding author.
E-mail address: Stephen.McVitie@glasgow.ac.uk (S. McVitie).

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structure, an asymmetric transverse domain wall (ATDW). This observation opens up the little-explored possibility of metastable states in CNWs and CNTs. Here, we use micromagnetic simulations to study the 3-D ATDW in more detail. We simulate all three DW types across a range of cylinder and tube dimensions to map their stability and derive a phase diagram. The internal and surface spin structure of each DW is characterised, then used to inform a discussion of the ease of identifying each DW experimentally.

2. Methods

Simulations of CNWs and CNTs were performed using the Nmag [15] finite element package due to its suitability to simulating curved structures, and checked against results from the object oriented micromagnetic framework [16] (OOMMF) package. The range of radii simulated was 5–50 nm and the length was fixed at 2 μm, sufficient to ensure that domain reversal occurs via DW propagation [12]. Material parameters typical of permalloy were used: magnetisation, $M_s = 8.6 \times 10^5\ \mathrm{A\,m^{-1}}$; exchange constant, $A = 1.3 \times 10^{-11}\ \mathrm{J\,m^{-1}}$; anisotropy constants, $K_1 = K_2 = 0$. Following an approach adopted previously [6,17], the damping parameter was set to $\alpha = 0.5$, which is artificially high but allows the simulation to relax quickly without otherwise compromising results. It is expected that phase diagrams for soft magnetic materials scale with the exchange length [18,19], so the results will be important for all systems where the energetic contribution of magnetocrystalline anisotropy is insignificant. The maximum node spacing for all Nmag simulations was 5 nm and the voxel size in OOMMF was $5 \times 5 \times 5\ \mathrm{nm}^3$, both of which were scaled to be less than the exchange length of 5.3 nm. Preliminary simulations showed that only three DW types could be stabilised, i.e. the TDW, BPW and ATDW. An important aspect of these simulations was to assess the metastability of walls, independent of the magnetic ground state. To achieve this, each of the three preliminary DW types was expanded/contracted and interpolated onto the required starting mesh, then allowed to relax to the local energetic minimum. Thus, we created a BPW, TDW or ATDW starting state for each radius in the range and determined whether or not it would stabilise.

3. Results and discussion

3.1. Cylindrical nanowire results

Fig. 1 shows a 3-D view and cross-section of each of the three head-to-head DW configurations: (a) TDW, (b) ATDW and (c) BPW. The colours represent the axial component of magnetisation, M_z, while the arrows show the surface spin configuration. The thinnest wires support a TDW, illustrated in Fig. 1(a), in which the magnetisation meets and rotates to lie transverse to the wire axis, breaking the cylindrical symmetry. In contrast to the 2-D transverse DW, in which the transverse region has two degenerate orientations, the transverse component of the (3-D) TDW has no fixed direction and can point at any azimuthal angle. This rotational degeneracy is evident in simulations that show a corkscrew motion of the DW about the wire axis as it propagates under the torque of applied field or spin-polarised current [9,13]. Much thicker wires relax to the BPW structure of Fig. 1(c), in which the magnetisation in the DW wraps around the wire axis. A cross-section through the wire shows a vortex-like structure, at the centre of which is a micromagnetic singularity or Bloch point. As discussed below, the external spin structure of the BPW is similar to that of the VDW, which is observed in CNTs. Previous simulations show that the dynamic behaviour of VDWs under an applied

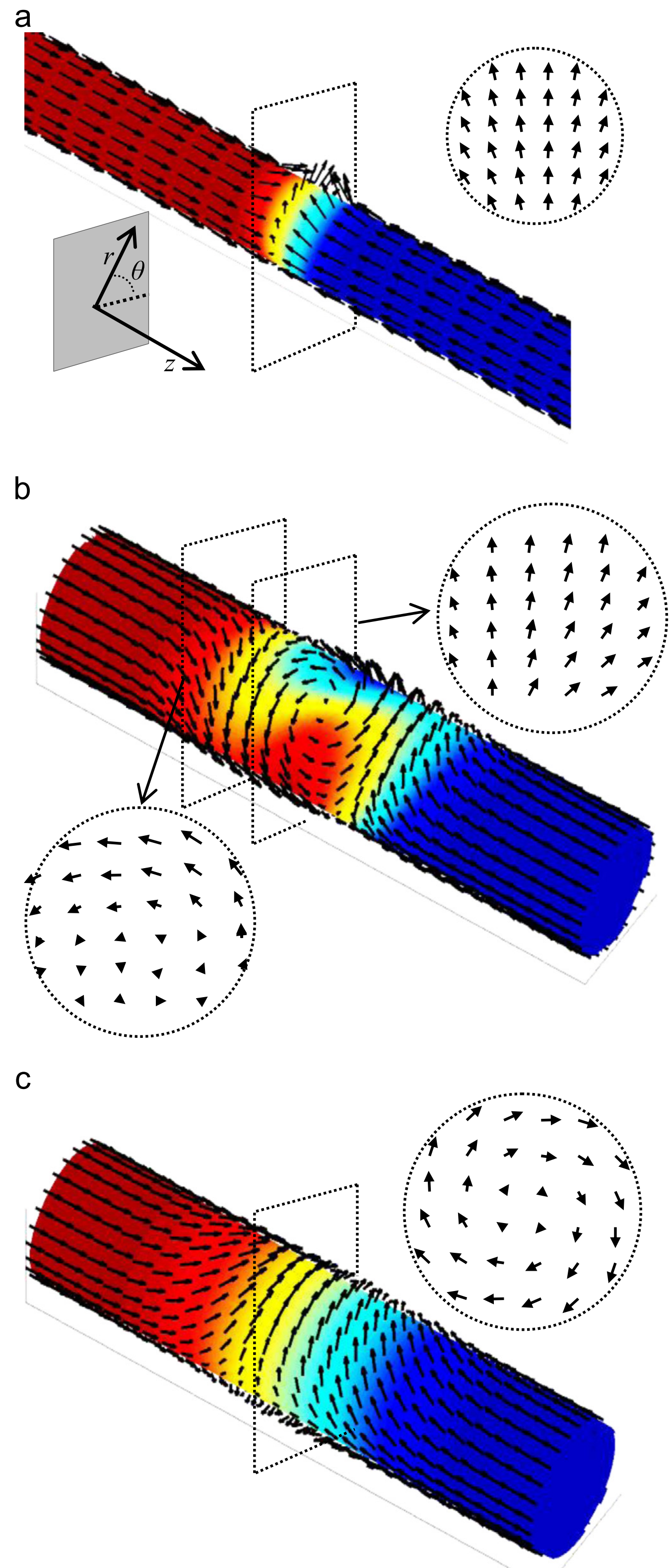

Fig. 1. The micromagnetic structure of (a) a transverse domain wall (TDW), (b) an asymmetric transverse domain wall (ATDW) and (c) a Bloch point domain wall (BPW) in soft ferromagnetic cylindrical nanowires. The external spin structure of the BPW is similar to that of the vortex domain wall (VDW) found in nanotubes. Colours indicate the magnitude of the axial component of magnetisation, M_z, in accordance with the arrows, which indicate the surface spin directions. The transition from red to blue therefore indicates the wall width. Cross-sections through the domain walls (in the r, θ plane), taken at the location of the wireframes, are inset.

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