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Fast domain wall dynamics in magnetic nanotubes: Suppression of Walker breakdown and Cherenkov-like spin wave emission

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We report on a micromagnetic study on domain wall (DW) propagation in ferromagnetic nanotubes. It is found that DWs in a tubular geometry are much more robust than ones in flat strips. This is explained by topological considerations. Our simulations show that the Walker breakdown of the DW can be completely suppressed. Constant DW velocities above 1000 m/s are achieved by small fields. A different velocity barrier of the DW propagation is encountered, which significantly reduces the DW mobility. This effect occurs as the DW reaches the phase velocity of spin waves (SWs), thereby triggering a Cherenkov-like emission of SWs. © *2011 American Institute of Physics*. [doi:10.1063/1.3643037]

In the last decade, the study of domain wall (DW) propagation in magnetic nanostructures has attracted much attention because of the potential applications in future magnetic devices such as race-track memory[1] and magnetic logical devices.[2] Fast and precisely controlled DW displacement is a prerequisite for the operations performed by such devices. However, the well-known Walker breakdown of DWs (Refs. 3 and 4) presents a major obstacle. Above a critical velocity, when the Walker breakdown occurs, the original DW structure collapses, resulting in an abrupt drop of the DW velocity. Afterwards the DW motion enters an irregular, oscillatory mode. Therefore, the Walker breakdown imposes a speed limit on the controlled and smooth motion of DWs. Complicated schemes have been proposed to prevent the Walker breakdown, such as a comb-like structure.[5] In this letter, we show an alternative approach which consists in using ferromagnetic nanotubes instead of flat strips as DW guides. By means of micromagnetic simulations, we found that soft-magnetic nanotubes can carry DWs with structures similar to those of flat strips, but with significantly superior stability. The increased stability is interpreted as a topological effect. The stability of DWs in this geometry is in fact high enough to completely suppress the Walker breakdown. A constant DW velocity above 1000 m/s is easily achieved by applying a small field. This high DW speed enables the observation of a previously unknown physical phenomenon in magnetic nanostructures: the *magnonic barrier* of DW propagation.

Most of the previous studies on DW propagation in magnetic nanostructures focused on flat strips, in which head-to-head (h2h) or tail-to-tail (t2t) DWs can form.[6] Two types of such DWs are the so-called transverse wall and the vortex wall.[6] Similarly, different types of h2h or t2t DWs can also form in cylindrical nanowires.[7] The DW type studied here is the vortex-like DW in cylindrical nanotubes.[8,9] Figure 1 shows the configuration of a h2h DW formed in a 4 μm long Permalloy tube with 60 nm outer diameter and 10 nm thickness. In the wall region, the magnetization circles around the tube, thereby forming a core-less vortex. Contrary to what could be deduced from its name, the vortex-like wall in nanotubes actually corresponds closely to the structure of a transverse wall in flat strips. This can be easily seen by artificially "unrolling" the tube into a flat strip as shown in Fig. 1(b). However, there exists an obvious difference between those two geometries, namely, the boundary. The lateral boundaries of a flat strip are removed by "rolling it up" into a tube. This change of boundary conditions has significant consequences for the DW dynamics, especially concerning the DW stability.[10] In flat strips, the Walker breakdown of a transverse wall is initiated by the nucleation of a vortex (or anti-vortex), which always enters from the lateral boundary.[4] This leads to a transformation to a(n) (anti-)vortex wall. In nanotubes, such a breakdown process is topologically forbidden, due to the lack of lateral boundary. In a detailed micromagnetic study, we found that a much higher threshold has

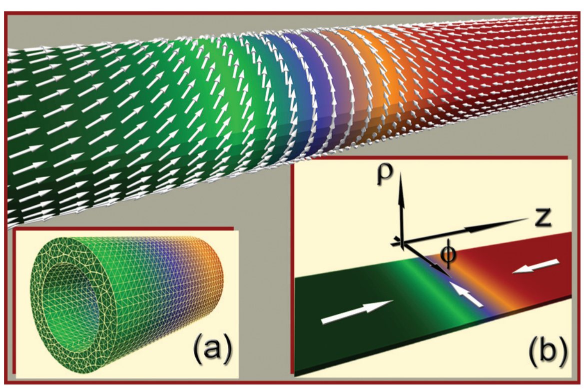

FIG. 1. (Color) A vortex-like DW formed in a 4 μm long Permalloy tube with 60 nm outer diameter and 10 nm thickness. The local magnetization is indicated by the white arrows. (a) A small section of the tube showing also the finite-element mesh. (b) A flat strip obtained by "unrolling" the tube. The white arrows indicate the magnetization near the DW.

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to be reached in order to destroy the structure of vortex-like DWs in nanotubes,[10] yielding a much higher DW stability compared to that in flat strips.

In the framework of micromagnetism, the magnetization dynamics of the DWs is described by the Landau-Lifshitz-Gilbert equation:

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M} \times \vec{H}_{\mathrm{eff}} + \frac{\alpha}{M_s}\left[\vec{M} \times \frac{d\vec{M}}{dt}\right], \tag{1}$$

where $\vec{M}$ is the local magnetization, M_s the saturation magnetization, γ the gyromagnetic ratio, $\vec{H}_{\mathrm{eff}}$ the effective field, and α the Gilbert damping factor. In our simulations, Eq. (1) is solved numerically using a finite-element method utilizing graphics processing units (GPUs).[11] Typical material parameters of Permalloy, $\mu_0 M_s = 1$ T, and exchange constant $A = 1.3 \times 10^{-11}$ J/m are used. The sample volume is discretized into irregular tetrahedrons with cell size of about 3 nm. The damping parameter is fixed to 0.02.

To drive the DW shown in Fig. 1, a magnetic field is applied along the $-$z direction. The resulting DW velocity as a function of field is plotted in Fig. 2(a). The dots indicate the data obtained from simulations. The blue and red lines are linear fits to the data in two distinct regions, respectively. In the low field region, the DW velocity increases linearly with the field, in agreement with the pre-breakdown regime in Walker's model. Above a critical velocity v_m about 1000 m/s, the slope of the velocity curve shows a sudden drop, i.e., an instantaneous decrease of the DW mobility. Note that after this change, the DW velocity continues to increase with larger fields. This is different from the velocity drop in the case of the Walker breakdown. In the high-field regime displaying a smaller mobility, the DW still moves with a constant velocity, contrary to the precessional DW motion occurring after the Walker breakdown. These results imply that the drop of the DW mobility observed in nanotubes is due to a different type of "speed limit" to the DW motion. This barrier, which was not reported before, is found to be directly related to the excitation of spin waves (SWs). The DW in fact strongly emits SWs when it moves faster than v_m. This effect is displayed in Fig. 2(b) which shows a snapshot of the magnetic configuration around the moving DW. Clearly, SW tails are attached both in front of and behind the DW. In the "unrolled" tube, these SWs appear as monochromatic planar waves. Both SW tails have well-defined yet different wave length. Figure 2(b) also displays the averaged azimuthal component of the magnetization in each cross-section of the tube ($\bar{m}_\phi$), showing how the SW tails are connected to the DW profile. Once stationary SW tails are established, they propagate together with the moving DW, hence forming a soliton-like unit moving with a constant velocity. At this stage, the system reaches a dynamic equilibrium, as can be best seen in a movie of the DW propagation.[12] This moving structure can be considered as a topological soliton with a very unusual asymmetric spatial profile.

For a deeper understanding of the characteristic SW emission mechanism, we numerically calculated the SW dispersion relation of the tube. Figure 3(a) shows the result, which agrees with an analytical calculation.[13] The phase velocity (v_p) of the SWs is then extracted from the dispersion, as shown in Fig. 3(b). One immediately sees that v_p has a minimum at around 1000 m/s, which coincides with the critical velocity v_m shown in Fig. 2(a). This fact elucidates the triggering mechanism of the SW emission, i.e., the matching of the DW velocity with the SW velocity. Such a magnonic limit of DW propagation was predicted analytically by Bouzidi and Suhl for the case of Bloch wall moving in extended films.[14] In weak ferromagnets, experimentally observed DW mobility change was attributed

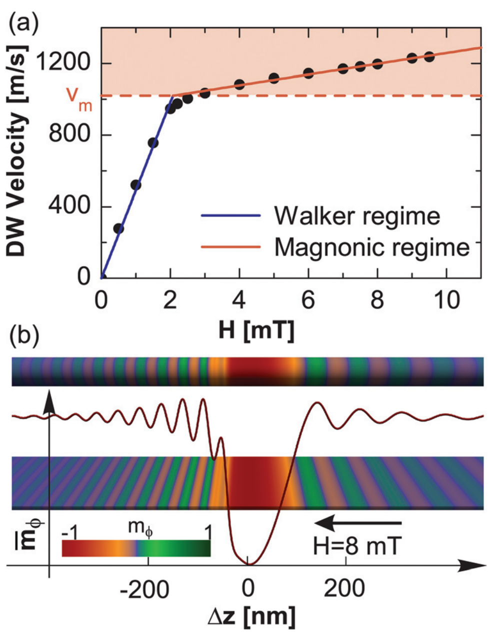

FIG. 2. (Color) (a) DW velocity as a function of field applied along $-z$ direction. The dots are the data obtained from simulations. The blue and red lines are linear fits to the data at two distinct regions, respectively. (b) A snapshot of SWs shown in both the tube and the corresponding "unrolled" one. Azimuthal component of the magnetization (m_ϕ) is indicated by the color coding. The curve is the plot of $\bar{m}_\phi$ in each cross-section of the tube.

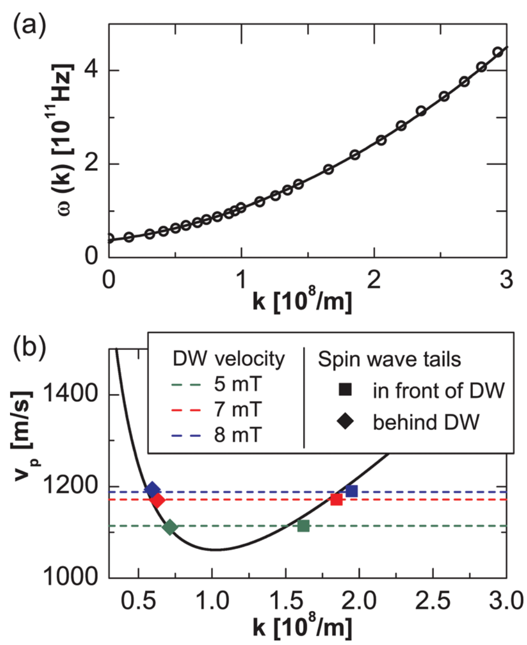

FIG. 3. (Color) (a) SW dispersion relation of a saturated tube obtained from numerical calculation. The line is a guide to the eye. (b) SW phase velocity extracted from the dispersion relation. Dashed lines indicate the DW velocities driven by three different fields. Data dots are for SW tails obtained from simulations.

to SW excitations.[15] However, detailed studies on this magnonic limit of DW motion are elusive, especially in the case of magnetic nanostructures. The reason is that the Walker breakdown usually takes place at velocities well below the SW velocity, thereby concealing the presence of a further speed limit at more elevated velocities. One also notices from Fig. 3(b) that there exist two spin-wave modes with the same v_p. This twofold degeneracy explains the bi-chromatic excitation of SWs as shown in Fig. 2(b). For a DW moving with a certain velocity v, the two SW tails attached to it are originated from the two SW modes sharing the same v_p that is identical to v. As the DW velocity changes, frequencies of the SW tails change accordingly to match their v_p with the DW velocity. This is illustrated in Fig. 3(b), where three different DW velocities are indicated by the dashed lines. Each line crosses two data points, corresponding to the two SW tails. This demonstrates that the matching of the SW velocity to the DW velocity is decisive for this effect. Furthermore, the change of the wave length of the SW tails follows the $v_p(k)$ curve derived from the SW dispersion. Another interesting feature of the SW emission is that the SW tail in front of the DW always has shorter wave length than the one behind. This spatial separation is due to the dispersion effect and the different group velocities of the two SW tails. The match of the SW and DW velocity implies the softening of the SW modes in the moving frame of the DW, which is clearly shown in a movie taken by a camera following the DW motion.[12] Therefore, the spontaneous emission of SWs by the DW can be attributed to a soft-mode induced instability, which agrees with Bouzidi and Suhl's model.[14] This type of emission, only occurring when the DW velocity reaches the SW velocity, is fundamentally different from another DW motion damping mechanism by SWs, in which SWs are emitted as the "wake" of a moving DW.[16]

The DW mobility drop can be interpreted as the consequence of an increase of the DW mass. The mass of the DW is defined by the energy increase of a moving DW compared to a static one.[17] In the magnonic regime, extra mass is added to the DW by the attachment of SW tails. This mechanism of acquiring mass is analogous to that of elementary particles interacting with the Higgs field in the standard model. In a more general physical context, the magnonic limit of DW motion is equivalent to the sound barrier of aircrafts or the Cherenkov radiation emitted by highly energetic charged particles.[18] Such effects occur when particles traverse a dispersive medium at a speed superior to the phase velocity of the waves propagating in this medium.

To conclude, we numerically demonstrated that a magnonic barrier of DW motion can occur in magnetic nanotubes. This effect can be considered as a speed limit to the DW propagation besides the Walker breakdown. The possibility to sustain stable DWs at large and constant propagation speed makes magnetic nanotubes as good candidates for devices based on DW displacement. In addition, the supermagnonic DWs provide a source for emitting strong and tunable SWs. Given the feasibility of the fabrication of such magnetic nanotubes,[19,20] the experimental investigation of the DW dynamics in those structures is promising.

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