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Research articles

Dynamics of vortex domain walls in ferromagnetic nanowires – A possible method for chirality manipulation

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ABSTRACT

The dynamic behaviors of vortex domain walls (VDWs) in ferromagnetic nanowires driven by a magnetic field above Walker breakdown field (H_w) were investigated using micromagnetic simulation. It was found when nanowire has proper geometrical dimensions, the VDW may oscillate in a chirality invariant mode or a chirality switching mode depending on applied field and damping constant. At fixed damping constant, the oscillation mode can be controlled by applied field – with the increase of applied field, the oscillation of VDW change from a chirality invariant mode to a variant one. As the oscillation of VDW changes from chirality invariant regime to chirality switching regime, the oscillation frequency and amplification will undergo an abnormal change, which may offer a fingerprint for the switch of oscillation mode. Our finding proposes a simple way to control the chirality of a VDW by properly manipulating nanowire geometry and applied field, which may have important applications in VDW-based devices.

1. Introduction

In recent years, extensive studies have been carried out to unveil static and dynamic properties of domain walls (DW) in ferromagnetic nanostructures, due to the related fundamental physics aspects as well as the technological applications, including memory [1–7] and logic [8–10] devices, and nanowire based microwave generators [11]. A vortex domain/domain wall can be characterized by the polarity of vortex core (VC), and the curling direction of the in-plane magnetization defined as chirality. The combinations of polarity and chirality provide four different vortex states, making the vortex spin structures more promising for applications in next-generation memory and logic devices. Most recently, vortex racetrack memory [6] and vortex domain wall logic devices [8] based on magnetic nanowire structures were proposed. Realization of those proposal depends on the ability to manipulate the chirality and the polarity of the DWs. Thus it makes great sense to investigate how the state of a VDW changes in a nanowire during its dynamic process from the stand point of basic physics and applications.

In a planar nanowire, the four vortex states are equally stable, it is not easy to change them from one to another. For example, to change the vortex state statically, a very large magnetic field along width or thickness is needed. However, the state change can be much easier achieved dynamically. It is known that the position of a VDW driven by a magnetic field above the critical value, the Walker field $H_{w,}$ oscillates in spatial directions along the nanowire and perpendicular to it [12–17]. During the oscillatory motions, at either edge of width, the VDW switches between two states. The problem, however, is that these studies suggested that only polarity of a VDW changes, while the chirality doesn't.

In recent years, some efforts have been devoted to manipulating the chirality of a VDW.J. A. Otalora reported a method to manipulate the chirality of a VDW in cylindrical nanowires using proper magnetic field pulses [18]; E. S. Wilhelm et al. suggested that the Magnetic domains forming at the end of a nanowire could be used to control the chirality [19]; K. Omari found that sharp corners of nanowires played a role in rectifying the chirality of VDW [20]; Besides, geometric defects like square or triangle notches were also proposed to be alternative ways for chirality manipulation [21–23]; Most recently, defects such as asymmetric Y-branches was also proposed for tuning chirality [24]. However, these methods may involve complicated designs and fabrication technologies for nanowire devices.

In this work, we used micromagnetic simulation to study the dynamics of VDWs in planar permalloy nanowires driven by a magnetic field above the Walker field. The influences of Gilbert damping constant, magnetic field, and geometry dimension were

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investigated. We found that in nanowires with proper dimensions, the chirality can be changed simply by adjusting magnetic field or damping constant. Our finding proposes a possible way to manipulate chirality of VDWs in nanowires.

2. Simulation method

The dynamics of VDWs in nanowires were carried out using the framework of OOMMF [25] codes, based on the Landua-Lifshitz-Gilbert equation.

In our simulations, planar permalloy nanowires were used with a saturation magnetization of $M_s = 8.6 \times 10^5$ A/m and exchange constant $A = 1.3 \times 10^{-11}$ J/m. The uniaxial anisotropy (K) was set as zero. The damping constant, α, varied from 0.01 to 0.03. The length (L), width (W), and thickness (T) of each nanowire were set along the x, y, and z axes, respectively. Mean while L, W, and T satisfied the condition $L \gg W > T$. The size of the mesh size was set to 4 nm × 4 nm × T. To produce the initial VDW, a thin wall with spins on either side pointing to opposite directions along the x-axis was first created in the middle of the wire, and allowed to relax until a stable DW formed [11]. The obtained DW was then used as the initial DW state in the nanowire. To investigate the dynamic behaviors of the VDWs, in all simulations, a driving magnetic field (H) was applied along nanowire length (in + x direction).

3. Results and discussion

The dynamics of a VDW in a nanowire with W = 200 nm and T = 15 nm was first investigated under different applied fields. Fig. 1(a) shows the changes of normalized magnetization components (m_x and m_y) as functions of time (t) when H = 1.15 mT and 2.2 mT. The damping constant is kept at 0.01. As can be seen, in either case, besides an overall drift, the VDW oscillates along x axis. This kind of periodic oscillation is a typical dynamic behavior of a VDW in a regime above Walker breakdown. When driven by a field above Walker field (H_w), the core of a VDW will oscillate back and forth along nanowire length, and in the meanwhile, it will oscillate up and down along nanowire width as shown in the insert of Fig. 1(a). However, when comparing the m_x vs t and m_y vs t curves under 1.15 mT and 2.2 mT fields, we find that the oscillation modes of the DW under these two fields are different. When H = 2.2 mT, the peaks of m_x vs t curve are always the same in shape, and the positive peaks and negative peaks in m_y vs t curve are symmetric. As a result, the period of longitudinal oscillation (along nanowire length) is half of that lateral oscillation (along nanowire width). We call this oscillation mode as mode 1. While as H = 1.15 mT, two neighbored peaks of m_x have detectably different shapes. If the small difference between two neighbored peaks is taken into account, the period of the longitudinal oscillation is found to be twice the interval between the peaks. Note that, the positive peaks and negative peaks of m_y vs t curve are also not completely symmetric. The periods of oscillations along x and y directions are equal in this case. We may define this kind of oscillation mode as mode 2. Both oscillation modes were also observed when varying damping constant at fixed applied field. Fig. 1(b) shows the changes of m_x and m_y as functions of t for α = 0.01 and α = 0.02 when the applied field is kept at 3 mT. It is obvious that the neighbored peaks of m_x are the same in shape when α = 0.01 (mode 1), but different when α = 0.02 (mode 2). From the insert of Fig. 1(b),

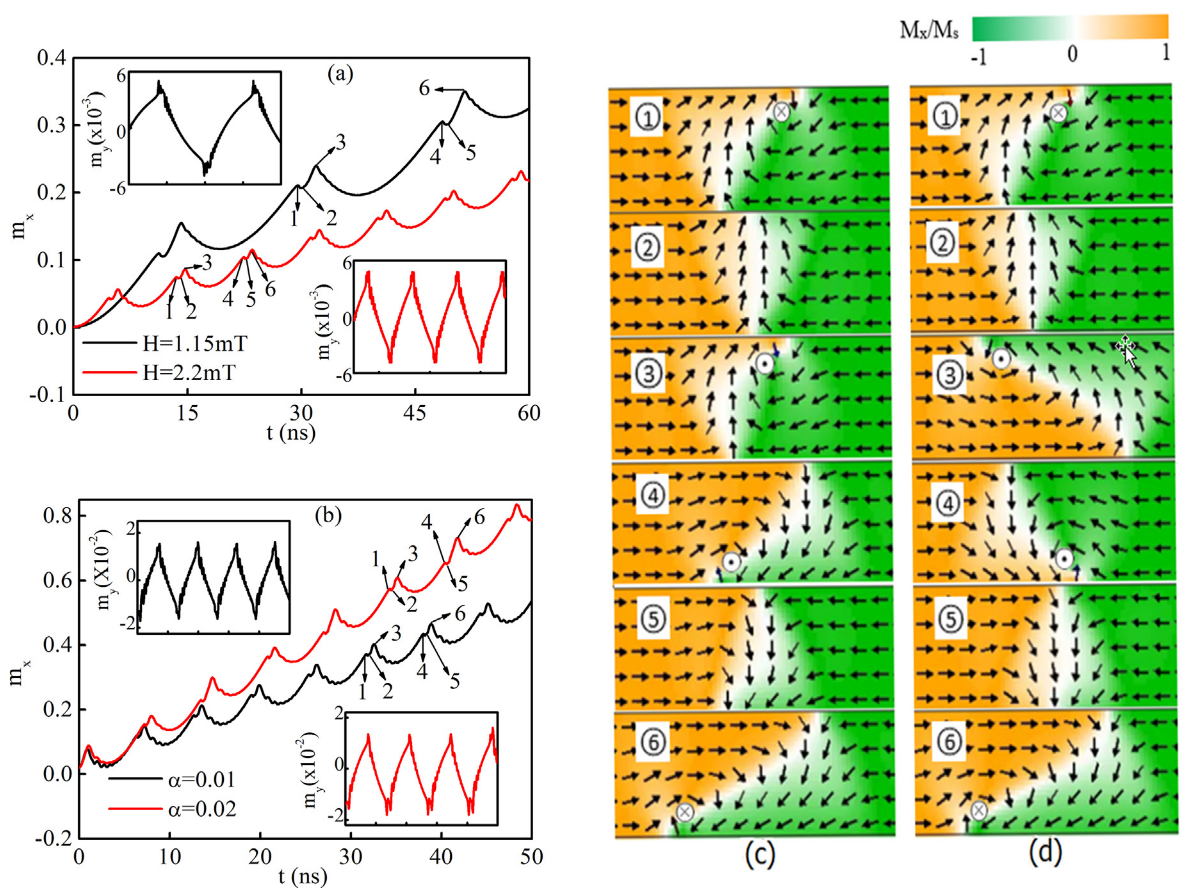

Fig. 1. (a) Normalized m_x and m_y (insets) as functions of time for cases of H = 1.15 mT and H = 2.2 mT with α = 0.01. (b) Normalized m_x and m_y (insets) as functions of time for cases of α = 0.01 and α = 0.02 at H = 3 mT. Snapshot images of instantaneous magnetization configurations for α = 0.02 (c) and α = 0.01 (d).