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Magnetic field driven domain-wall propagation in magnetic nanowires ☆

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ABSTRACT

The mechanism of magnetic field induced magnetic domain-wall (DW) propagation in a nanowire is revealed: A static DW cannot exist in a homogeneous magnetic nanowire when an external magnetic field is applied. Thus, a DW must vary with time under a static magnetic field. A moving DW must dissipate energy due to the Gilbert damping. As a result, the wire has to release its Zeeman energy through the DW propagation along the field direction. The DW propagation speed is proportional to the energy dissipation rate that is determined by the DW structure. The negative differential mobility in the intermediate field is due to the transition from high energy dissipation at low field to low energy dissipation at high field. For the field larger than the so-called Walker breakdown field, DW plane precesses around the wire, leading to the propagation speed oscillation.

Magnetic domain-wall (DW) propagation in a nanowire due to a magnetic field [1–5] reveals many interesting behaviors of magnetization dynamics. For a tail-to-tail (TT) DW or a head-to-head (HH) DW (shown in Fig. 1) in a nanowire with its easy-axis along the wire axis, the DW will propagate in the wire under an external magnetic field parallel to the wire axis. The propagation speed v of the DW depends on the field strength [3,4]. There exists a so-called Walker's breakdown field H_W [6]. v is proportional to the external field H for $H < H_W$ and $H \gg H_W$. The linear regimes are characterized by the DW mobility $\mu \equiv v/H$. Experiments [1–3] showed that v is sensitive to both DW structures and wire width. DW velocity v decreases as the field increases between the two linear H-dependent regimes, leading to the so-called negative differential mobility phenomenon. For $H \gg H_W$, the DW velocity, whose time-average is linear in H, oscillates in fact with time [6,3].

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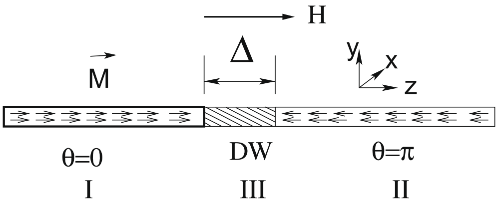

Fig. 1. Schematic diagram of a HH DW of width Δ in a magnetic nanowire of cross-section A. The wire consists of three phases, two domains and one DW. The magnetization in domains I and II is along +z-direction ($\theta = 0$) and $-z$-direction ($\theta = \pi$), respectively. III is the DW region whose magnetization structure could be very complicate. $\vec{H}$ is an external field along +z-direction.

It has been known for more than fifty years that the magnetization dynamics is governed by the Landau–Lifshitz–Gilbert (LLG) [7] equation that is nonlinear and can only be solved analytically for some special problems [6,8]. The field induced domain-wall (DW) propagation in a strictly one-dimensional wire has also been known for more than thirty years [6], but its experimental realization in nanowires was only achieved [1–5] in recent years when we are capable of fabricating various nano structures. Although much progress [9,10] has been made in understanding field-induced DW motion, it is still a formidable task to evaluate the DW propagation speed in a realistic magnetic nanowire even when the DW structure is obtained from various means like OOMMF simulator and/or other numerical software packages. A global picture about why and how a DW propagates in a magnetic nanowire is still lacking.

In this paper, we present a theory that reveals the origin of DW propagation. Firstly, we shall show that no static HH (TT) DW is allowed in a homogeneous nanowire in the presence of an external magnetic field. Secondly, energy conservation requires that the dissipated energy must come from the energy decrease of the wire. Thus, the origin of DW propagation is as follows. A HH (TT) DW must move under an external field along the wire. The moving DW must dissipate energy because of various damping mechanisms. The energy loss should be supplied by the Zeeman energy released from the DW propagation. This consideration leads to a general relationship between DW propagation speed and the DW structure. It is clear that DW speed is proportional to the energy dissipation rate, and one needs to find a way to enhance the energy dissipation in order to increase the propagation speed. Furthermore, the present theory attributes a DW velocity oscillation for $H \gg H_W$ to the periodic motion of the DW, either the precession of the DW or oscillation of the DW width.

In a magnetic material, magnetic domains are formed in order to minimize the stray field energy. A DW that separates two domains is defined by the balance between the exchange energy and the magnetic anisotropy energy. The stray field plays little role in a DW structure. To describe a HH DW in a magnetic nanowire, let us consider a wire with its easy-axis along the wire axis (the shape anisotropy dominates other magnetic anisotropies and makes the easy-axis along the wire when the wire is small enough) which is chosen as the z-axis as illustrated in Fig. 1. Since the magnitude of the magnetization $\vec{M}$ does not change in the LLG equation [8], the magnetic state of the wire can be conveniently described by the polar angle $\theta(\vec{x}, t)$ (angle between $\vec{M}$ and the z-axis) and the azimuthal angle $\phi(\vec{x}, t)$. The magnetization energy is mainly from the exchange energy and the magnetic anisotropy because the stray field energy is negligible in this case. The wire energy can be written in general as

$$\begin{aligned} E &= \int F(\theta, \phi, \vec{\nabla}\theta, \vec{\nabla}\phi) d^3\vec{x}, \\ F &= f(\theta, \phi) + J[(\vec{\nabla}\theta)^2 + \sin^2\theta(\vec{\nabla}\phi)^2] - MH\cos\theta, \end{aligned} \tag{1}$$

where f is the energy density due to all kinds of magnetic anisotropies which has two equal minima at $\theta = 0$ and π ($f(\theta = 0, \phi) = f(\theta = \pi, \phi)$), J-term is the exchange energy, M is the magnitude of magnetization, and H is the external magnetic field along z-axis. In the absence of H, a HH static DW that separates $\theta = 0$ domain from $\theta = \pi$ domain (Fig. 1) can exist in the wire. The domain structure is determined by the equations