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Current-induced domain wall motion in magnetic nanowires with spatial variation

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ABSTRACT

We model current-induced domain wall motion in magnetic nanowires with the variable width. Employing the collective coordinate method we trace the wall dynamics. The effect of the width modulation is implemented by spatial dependence of an effective magnetic field. The wall destination in the potential energy landscape due to the magnetic anisotropy and the spatial nonuniformity is obtained as a function of the current density. For a nanowire of a periodically modulated width, we identify three (pinned, nonlinear, and linear) current density regimes for current-induced wall motion. The threshold current densities depend on the pulse duration as well as the magnitude of wire modulation. In the nonlinear regime, application of ns order current pulses results in wall displacement which opposes or exceeds the prediction of the spin transfer mechanism. The finding explains stochastic nature of the domain wall displacement observed in recent experiments.

1. Introduction

A magnetic domain wall (DW) interacts with spin-polarized electrical current and as a result a displacement is induced by the application of a current [1,2], showing the possible electrical control of the magnetization direction [3–7]. For both technological and fundamental reasons the effect of electrical current in such nonuniform spin texture attracts much attention [8–12]. This physics is reflected not only in possible spintronics devices [13–15] but also in new concepts such as spin-motive forces [16]. Recently, we revealed that such current-drives cannot be identified with any equivalent field-drives by investigating DW creep motion experimentally and theoretically in the light of the universality classes [17].

The current-induced DW motion is now well-understood in terms of the spin transfer mechanism [2,18–27]; the conservation of angular momentum between conducting and localized spins results in the DW propagation in the direction of the electrons' flow. While a number of experimental results support this scenario [3–6,28–33] some counter examples have been reported for DWs trapped in nonstraight wires [30,34,35]. Since spatial modulation of the sample gives rise to an alternating potential-energy profile for the DW [36] the current-induced dynamics can be strongly influenced by shape-variation of the nanowire. The wire-shape patterning [37–39] as well as deliberately introduced defects in nanowires [40–42] demonstrate geometrical control of the DW's position and direction of the motion, which is crucial in, e.g., a precise loading of DWs in memory devices. Combining curved nanowires with DC magnetic fields, measurements of the DW resonance induced by AC [7,44,43] and pulsed [34,44] currents have been performed. Thus, detailed analysis of how the DW negotiates with the shape effects in the presence of the spin-transfer torque becomes more important. However, due to nonlinear nature arising from the magnetic anisotropy and the spatial nonuniformity, a basic understanding of the current-induced DW dynamics in magnetic nanowires with spatial variation still remains to be explored.

In this work, we perform analytical and numerical study of the shape effect on the DW dynamics by means of the collective coordinate method [45–47] which is widely adopted to visualize essential features of DW physics [8–11]. The magnitude and periodicity of spatial variation in a patterned wire are implemented by position dependence of effective magnetic fields as described below. Compared to more elaborated micromagnetic simulations [48] our approach provides a considerably concise computational method as well as a clear physical interpretation. Owing to these facts, it is possible to survey a wide range of the model parameters such as pulsed current density and duration. As an example, we study current-induced DW motion in nanowires with the periodically modulated width as shown in Fig. 1(a) and (b). The shape effect is reflected in periodic changes of the energy

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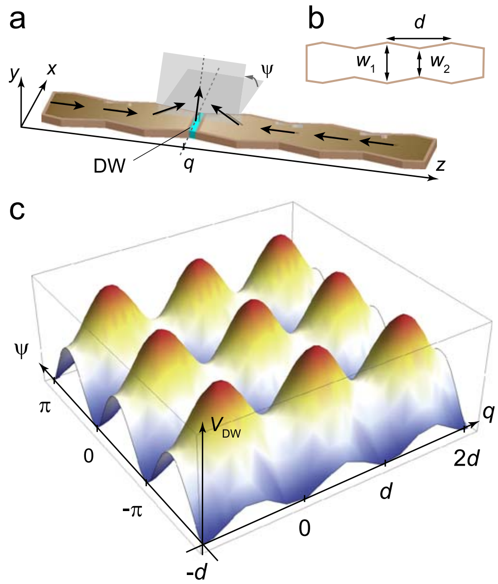

Fig. 1. (a) A schematic illustration of a thin ferromagnetic nanowire with the periodically modulated width containing a single domain wall (DW). The arrows indicate magnetization direction. The DW is characterized by two collective coordinates, i.e., q, the center position, and ψ, the tilt angle from the easy plane. (b) A top view of the patterned wire with $w_1 > w_2$, the widths, and d, the period of the modulation. The cross-sectional area is modeled by Eq. (5). (c) An energy landscape of the DW, $V_{\rm DW}$, given by Eq. (3) with (5) in the (q,ψ) phase space. The periodicity in each coordinate stems from the patterned wire and the magnetic anisotropy, respectively.

landscape which modify the local propagation field. For application of short current pulses, it is shown that the backward displacement of the DW occurs, opposing to the flow of electrons. This finding is relevant to a recent experimental observation [35].

In the next section we present our approach for calculating the DW dynamics, using the collective coordinate method. We then show how the effect of nanowire modulation can be accounted for. In Section 3, this method is applied to magnetic wires with a sinusoidally modulated width (modulation amplitude 20% and periodicity 1 μm). We calculate the DW displacement in the shaped nanowire varying the magnitude and duration of activation current pulses. We find three current density regimes depending on properties of the DW dynamics. We argue the results in terms of a trajectory of the collective coordinates in the DW energy landscape. Comparing with a recent experiment, a key feature of our calculations is explained. The final section is devoted to summary and conclusion.

2. Model

We consider a thin ferromagnetic nanowire composed of Permalloy (NiFe), which has the easy uniaxial and the hard out-of-plane magnetic anisotropies due to demagnetization fields. The hard and easy axes are respectively in y and z direction in our coordinate system as shown in Fig. 1(a). In this study, we use the one-dimensional model of magnetization dynamics along the z axis, assuming uniformity in the lateral directions (the x–y plane). In the light of this simplification, the dynamics of a single domain wall can be described by a set of the collective coordinates; the center position q and the tilt angle ψ of the DW plane relative to the easy x–z plane as indicated in Fig. 1(a). By means of these coordinates, the Landau–Lifshitz equation with the spin-transfer torque term [2,26] reduces to

$$\dot{q} = u + \frac{\Delta\gamma}{1+\alpha^2}\left[\alpha H + \frac{H_K}{2}\sin 2\psi\right], \tag{1}$$

$$\dot{\psi} = \frac{\gamma}{1+\alpha^2}\left[H - \alpha\frac{H_K}{2}\sin 2\psi\right], \tag{2}$$

where we define $\dot{q} = dq/dt$, γ the gyromagnetic ratio, α the damping constant, H_K is a perpendicular anisotropy field, and Δ is the wall width parameter. This model provides a quasiparticle picture of the DW [49]. External drives in this system are twofold [17,50–53]; an external magnetic field H along the z axis, and the spin transfer torque term [1,2,19–21] $u = m_j j$ due to the electrical current density j along the wire. In the latter, the current mobility is defined by $m_j = (Pg\mu_{\rm B})/(2eM_{\rm s})$, where P the spin polarization, g the g-factor, $\mu_{\rm B}$ the Bohr magneton, e the elementary charge, and $M_{\rm s}$ the saturation magnetization. It is important to note that the u-term does not derive from any actual potentials [26]. The model is appropriate for description of transverse domain walls while the dynamics of vortex domain walls can be interpreted in the one-dimensional model provided the anisotropy field, H_K, is properly adjusted. The DW displacement is independent of its chirality.

In the present study, the original version of the Landau–Lifshitz damping [54] is adopted, for which the relaxation properly lowers the DW energy and an intrinsic pinning is absent in the nature of the case [2,26,55]. Although inclusion of nonadiabatic spin torques and/or spin–orbit interactions is an interesting subject we focus on the effect of nanowire shape on the DW dynamics together with the main contribution due to the current. We have checked that those subleading effects does not modify the main features of our result qualitatively.

Due to competition of the exchange interaction and the magnetic anisotropy, DWs have a characteristic surface tension, σ. As well-known in the text book [46], energy minimization gives, $\sigma = \sigma_0(1+Q^{-1}\sin^2\psi)^{1/2}$, where $\sigma_0 = \sqrt{A_{\rm s}K_{\rm u}}$ with $A_{\rm s}$, the exchange stiffness constant, $K_{\rm u}$, the uniaxial anisotropy constant, and Q is the ratio of $K_{\rm u}$ to the perpendicular anisotropy constant. For a wire with the constant cross-sectional area, A, the surface energy, σA, does not depend on the DW position. In spatially nonuniform wires, however, A varies as the DW moves, giving rise to position dependence of the DW energy. For the long-wavelength modulation compared to the DW width, $\pi\Delta$, the DW energy can be given by

$$V_{\rm DW} = \sigma A(q), \tag{3}$$

apart from the Zeeman contribution. The gradient of $V_{\rm DW}$ with respect to q exerts a force acting on the DW [56]. This can be interpreted as the effective field,

$$H_{\rm shape} = -\frac{\sigma}{2M_{\rm s}}\frac{\partial}{\partial q}\ln A(q), \tag{4}$$

which depends on the position q (and also on ψ through σ). Thus, the shape effect can be included in the equations of motion Eqs. (1) and (2) by replacing H with $H + H_{\rm shape}$.

In order to understand the influence of the shape effect on the DW dynamics, we study a ferromagnetic nanowire with sinusoidally patterned edges as shown in Fig. 1(a). The cross-sectional area with a constant thickness h is expressed as

$$A(q) = hw[1 - r\cos(2\pi q/d)], \tag{5}$$

where the average width $w = (w_1 + w_2)/2$, the modulation amplitude $r = (w_1 - w_2)/2w$, with the maximum and minimum widths $w_1 > w_2$, and the sinusoidal period d as illustrated in Fig. 1(b). In the present study, we assume $d > \pi\Delta$ and $L \gg w > h$ where L is the wire length. Substituting Eq. (5) in Eq. (3), we obtain the periodic energy landscape shown in Fig. 1(c).