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Magnetic domain-wall velocity enhancement induced by a transverse magnetic field

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ABSTRACT

Spin dynamics of field-driven domain walls (DWs) guided by permalloy nanowires are studied by high-speed magneto-optic polarimetry and numerical simulations. DW velocities and spin configurations are determined as functions of longitudinal drive field, transverse bias field, and nanowire width. Nanowires having cross-sectional dimensions large enough to support vortex wall structures exhibit regions of drive-field strength (at zero bias field) that have enhanced DW velocity resulting from coupled vortex structures that suppress oscillatory motion. Factor of 10 enhancements of the DW velocity are observed above the critical longitudinal drive-field (that marks the onset of oscillatory DW motion) when a transverse bias field is applied. Nanowires having smaller cross-sectional dimensions that support transverse wall structures also exhibit a region of higher mobility above the critical field, and similar transverse-field induced velocity enhancement but with a smaller enhancement factor. The bias-field enhancement of DW velocity is explained by numerical simulations of the spin distribution and dynamics within the propagating DW that reveal dynamic stabilization of coupled vortex structures and suppression of oscillatory motion in the nanowire conduit resulting in uniform DW motion at high speed. The enhanced velocity and drive field range are achieved at the expense of a less compact DW spin distribution.

1. Introduction

A variety of recently proposed spintronic devices would use magnetic domain walls (DWs) confined by in-plane magnetized nanometer-scale magnetic conduits to store and process information [1–5]. Similar magnetic structures have been proposed for lab-on-a-chip platforms for manipulating and functionalizing magnetic nanoparticles, captured by DW stray fields [6–8]. The viability of DW-based spintronic technologies rests largely on the DW spin distributions and on how fast DWs can be propelled in nanoscale structures. It has recently been experimentally demonstrated [9] that DWs driven by longitudinal magnetic fields along a ferromagnetic nanowire exhibit velocity breakdown behavior: Wall velocity increases with increasing drive field but above a critical field, the velocity drops abruptly. This counter-intuitive behavior results from the nucleation and gyrotropic motion of vortices within a DW, resulting in oscillatory DW displacements that dissipate energy that would otherwise go into displacing the wall [10].

A key theoretical result of DW dynamics is the existence of two regimes of wall propagation separated by a critical field H_c [11,12]. Drive fields H below H_c yield DW propagation that obeys a linear mobility relationship:

$$v(H) = \mu H \tag{1}$$

where v is the DW velocity and μ is the mobility. Drive fields $H > H_c$ produce a region of negative differential mobility followed by a second region of asymptotic linear mobility (H â ª¢ H_c) with a significantly smaller mobility parameter than predicted (and observed) for $H < H_c$. In the analytical one-dimensional (1D) model [11,12], a transverse DW has a mobility given by

$$\mu = \frac{\gamma\Delta}{\alpha} \quad (H < H_W), \tag{2a}$$

$$\mu = \frac{\alpha\gamma\bar{\Delta}}{1+\alpha^2} \quad (H > H_W). \tag{2b}$$

In Eq. (2), γ is the gyromagnetic ratio, Δ (or $\bar{\Delta}$) is the (average) DW width, and α is the Gilbert damping parameter. In the 1D model, the critical field is called the Walker field, H_W. The parameter H_W specifies the onset of precessional spin motion that drives oscillatory DW motion and accounts for the reduced average velocity and

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lower mobility. Numerical simulations of static and dynamic DW configurations in rectangular cross-section nanowire structures have shown that the spin configuration within a DW is governed by the nanowire cross-sectional parameters. Thin narrow wires support simple transverse wall (TW) spin structures whereas wider and thicker walls support more complex vortex wall (VW) structures.

Mobility measurements of DW propagation in permalloy (Py) nanowires [9] manifest the qualitative behavior predicted by the 1D model, but the measured H_c is ~10 Oe, a factor of 10 lower than the 1D model value ($H_W \approx 100$ Oe); and the corresponding maximum velocity, $v_c \equiv v(H_c)$, is a factor of 10 lower than $v(H_W)$. Numerical simulations of spin distributions within the propagating DWs account for this large discrepancy: the energy barrier for (anti) vortex formation is overcome at values of H far below the onset of precessional motion given by the Walker field H_W. This (anti) vortex formation provides the mechanism for the onset of the low-mobility regime that limits DW propagation velocities to $v_c \sim 100$ m/s at moderate applied fields. At sufficiently high longitudinal drive fields, the DW velocity can reach values equal to or exceeding the value at H_c.

Recent numerical simulation studies have explored possible ways to overcome velocity breakdown in nanowires by inhibiting (anti) vortex generation. The first [10] of these predicted that edge roughness of an appropriate scale should disrupt antivortex formation at the wire edges. In a perfectly smooth wire, each nucleated antivortex core was observed to be gyrotropically driven into and across the wire, resulting in velocity breakdown behavior. When edge roughness on the scale of the antivortex core diameter (~10 nm) was added to the simulations, the inhomogeneous local magnetostatic fields perturbed the nucleated antivortex cores, resulting in annihilations via spin-wave excitations before they were able to enter and slow the DW, thus eliminating the usual drop in velocity above H_c. However, the DW velocity remained self-limited to v_c even at fields exceeding H_c. As the DW speed approached v_c, an edge antivortex was generated and its subsequent decay dissipated energy, slowing the wall velocity.

A similar result was achieved in the simulations of Lee et al. [13] using a different means. The simulated mobility of a DW in an isolated Py nanowire was compared to the DW mobility in a Py nanowire lying atop a perpendicularly-magnetized underlayer. Above H_c, antivortex cores were nucleated at the edge of a propagating TW, but the stray field from the underlayer caused each core to be quickly expelled before it entered the wire. Again, however, the DW velocity increased with increasing field up to H_c, beyond which the wall velocity reached a plateau. Hence, while these studies suggest ways to partially suppress velocity breakdown, they did not predict an increase in the maximum velocity of DW propagation.

A possible route to enhancing the critical velocity was suggested in the numerical studies of Kunz and Reiff [14] and Bryan et al. [15], which examined the effects of a transverse in-plane bias field H_{bias} on the dynamics of a TW. A related analytical study by Sobolev et al. [16] addressed the effects of transverse fields on the motion of (Bloch) DWs. A bias field, applied transverse to the wire axis, does not directly drive DW motion, but it does change the width Δ of the wall. When the field is aligned with the net wall moment, Δ is increased; when it is antiparallel to the wall moment, Δ is decreased. An increase of Δ results in an enhancement of DW velocity, $v \propto \Delta$, as expected from the 1D model [11,12] (Eq. (2)). The velocity increase is modest, however, up to only ~20%, and any benefit ceases beyond the breakdown drive-field threshold. In the oscillatory regime ($H > H_c$) Bryan et al. found a region of enhanced DW velocity around $H = 100$ Oe for both positive and negative transverse bias fields: the average DW velocity recovers to a value slightly above the peak value achieved at H_c. Glathe et al. [17,18] have reported corresponding enhancements.

In this paper, we describe the effects of a transverse bias field on nanowire guided DW dynamics in the case of wider wires that support more complex DW structures including vortex, vortex–antivortex and stretch-mode structures [19–23]. We find strikingly different behavior from that predicted for wires of smaller cross section. While simulations show that high-mobility regions of DW propagation exist for $H > H_c$ in both narrow (TW) and wider (VW) nanowire conduits, we show that the wider conduits exhibit much higher transverse-field induced enhancement of DW velocity. We also extend prior numerical simulations of nanowire-guided TW structures to higher drive fields.

2. Experiment

The 490 nm wide 35 μm long nanowire was fabricated by focused ion milling from a Ta(3 nm)/Py(20 nm)/Ta(5 nm) trilayer that had been sputter-deposited onto an oxide-coated Si substrate [Fig. 1(a)]. One end incorporated a large magnetic pad that served as a nucleation and injection source of DWs; the other end was tapered into a point to inhibit DW nucleation. High-bandwidth magneto-optic polarimetry [24] was used to measure the time-dependent DW displacements under a combination of longitudinal drive field H and transverse bias field H_{bias} strengths. The average DW velocity was determined from time-of-flight measurements. The polarimeter beam was focused at 1 μm-step multiple locations along the nanowire and was used to detect the DW as it propagates across each beam spot location. Arrival transients at 1 μm-interval locations were averaged over many injections at a prescribed set of bias and drive fields, and the average velocity was obtained from the distance and DW time-of-flight [9]. Systematic studies of the measured magneto-optical transient as a function of longitudinal drive field and polarimeter beam placement along the nanowire have shown that the transient signal also detects instantaneous velocity and can be used to detect the DW oscillations that occur in the precessional regime [22]. Numerical simulations of DW propagation along nanowires with transverse bias, as well as the experiments described in following sections (and in Fig. 4), both reveal evidence of "stretch" modes that propagate with novel dynamics and that are characterized by a DW spin distribution that extends to micron scale widths.

3. Micromagnetic simulations

Micromagnetic simulation was used to understand the experimental results. The simulations were carried out using a version of LLG Micromagnetics Simulator developed by Scheinfein [25] that has been adapted to the University of Texas Lonestar Cluster [26] (a 5840 processor 64 bit Linux-based system capable of 62 TFLOP/sec peak performance). The numerical simulations were carried out using the accepted parameters for permalloy ($Ni_{80}Fe_{20}$); saturation magnetization $M_s = 800 \times 10^3$ A/m, exchange constant $A = 1.0 \times 10^{-11}$ J/m, and Gilbert damping constant $\alpha = 0.01$. The unit cell size and integration time step were $4 \times 4 \times 20$ nm^3 and 0.3 ps by using the fourth order predictor–corrector integrator, respectively. (There was no difference in the simulated mobility curves with integration time step of 0.1 – 0.4ps.) To reduce computational time, moving boundary conditions (with the simulation system size $L = 8$ μm) were used, but selected moving boundary condition results were compared with corresponding results of fixed boundary condition (with the simulation system size $L = 20$ μm) to ensure accuracy. The average DW velocities (plotted as numerical simulations of mobility curves in Fig. 2) were determined by time averages of effective spin