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Current Perspectives

Current-induced domain wall motion

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Abstract

The present understanding of domain wall motion induced by spin-polarized electric current is assessed by considering a subset of experiments, analytical models, and numerical simulations based on an important model system: soft magnetic nanowires. Examination of this work demonstrates notable progress in characterizing the experimental manifestations of the "spin-torque" interaction, and in describing that interaction at a phenomenological level. At the same time, an experimentally verified microscopic understanding of the basic mechanisms will require substantial future efforts, both experimental and theoretical.
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1. Introduction

In 1978, Luc Berger predicted that a spin-polarized current should apply a torque to a magnetic domain wall [1]. In a series of remarkable but only recently appreciated works, Berger set the theoretical [1–4] and experimental [5–7] groundwork for what is now a burgeoning industry in magnetism research. This article will present our perspectives on what progress has been made in the intervening years and what key questions remain unanswered. This is by no means an exhaustive review of current-induced domain wall motion (CIDWM). Rather, it is an attempt to identify inconsistencies and unresolved issues so as to assess the present state of understanding and help guide future efforts.

We shall focus on the current-driven motion of domain walls in submicron "wires" fabricated from soft magnetic thin films. The scope of the assessment is limited to examining a subset of work that highlights key experimental results and their interpretation within existing models. This paper is organized into three sections. Section 2 outlines general features of domain wall physics as described by the most prominent phenomenological models. The aim is to summarize the predicted effects of spin-polarized current on domain walls in terms of specific model parameters, without delving into the microscopic justifications for those parameters. Section 3 then focuses on experiments that have probed various aspects of spin-transfer torque (STT) and domain walls, describing what the experiments do tell us and, just as important, what they do not. Finally, Section 4 attempts to put these experimental results into perspective.

2. Spin torque and domain walls

CIDWM has been documented in materials ranging from magnetic semiconductors [8] to perpendicular-anisotropy superlattices [9], but the most widely studied material by far has been Permalloy ($Ni_{80}Fe_{20}$). A combination of desirable properties, including low anisotropy and near-zero magnetostriction, has led to its decades-long ubiquity in magnetic storage technology. As a result, it is among the best-characterized magnetic alloys and has become a benchmark system in magnetization dynamics studies.

Early work in CIDWM involved domain walls in extended films, but in recent years, the focus has shifted to "nanowires". In addition to their potential role in future

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devices, ferromagnetic nanowires offer greater control of domain walls, they are ideally suited to carrying current, and their dimensions are amenable to numerical studies. In these structures, magnetic domains lie along the wire axis, and are separated by head-to-head or tail-to-tail domain walls. The spin structures within these walls are reasonably well understood, and approximate analytical models describing their dynamics were derived long ago [10]. Where the analytical models fail, numerical integration of the Landau–Lifshitz–Gilbert (LLG) equation takes over in providing further insight. LLG simulations have shown that domain walls in nanowires can exhibit relatively simple or highly complex behavior, and some of this behavior has been borne out by experiment.

The effects of electric current have been treated by the addition of two current-induced torque terms to the LLG equation [11–15]. This section will outline the phenomenology of domain wall motion in nanowires and the roles played by these torques. As we write from an experimental point of view, we take a heuristic approach to the theory with the aim of identifying the observable manifestations of STT on domain wall motion. This section will serve as a guide for a later critical analysis of experiments.

2.1. Forms of spin torque

With current density j along $\hat{\mathbf{x}}$, the time evolution of the (normalized) magnetization vector $\mathbf{m}$ may be described by the LLG equation:

$$\dot{\mathbf{m}} = -\gamma\mathbf{m}\times\mathbf{H}_{eff} + \alpha\mathbf{m}\times\dot{\mathbf{m}} - v_j\frac{\partial\mathbf{m}}{\partial x} + \beta v_j\mathbf{m}\times\frac{\partial\mathbf{m}}{\partial x}. \tag{1}$$

The first term on the right accounts for torque by the effective field $\mathbf{H}_{\mathrm{eff}}$ (including applied, demagnetizing, anisotropy, and exchange fields). The second term describes (Gilbert) damping torque, parameterized by a dimensionless α. The final two terms, where $v_{\mathrm{j}} = \eta j$, express current-induced torques on $\mathbf{m}$ about two mutually orthogonal axes in a region of nonuniform magnetization. These torques are most commonly termed *adiabatic* and *nonadiabatic*, respectively [11–16], and the parameters η and β characterize their strength.

The most widely agreed upon interaction between a spin-polarized current and a domain wall is adiabatic STT [1,11,12,14]. A conduction electron traversing a domain wall experiences a torque that compels its spin to follow the local magnetization direction. In so doing, its spin "flips" as it crosses a wall separating two opposing domains. In this adiabatic process, the consequent change in electron spin angular momentum is transferred to the (localized) spins within the wall. The torque associated with this spin transfer is the adiabatic term in Eq. (1). Berger's original description [1], as well as most subsequent work [11,12,14], arrives at

$$\eta = \frac{g\mu_{\mathrm{B}}P}{2eM_{\mathrm{s}}}. \tag{2}$$

Here g, μ_{B}, and e are the Landé factor, Bohr magneton, and electron charge, respectively, M_{s} is the saturation magnetization, and P is the conduction electron spin polarization. For Permalloy, $\eta = P\times 7\times 10^{-11}\,\mathrm{m^3/C}$, or a velocity of $P\times 7\,\mathrm{m/s}$ per $10^{11}\,\mathrm{A/m^2}$ of current. The value of P is not well known, but estimates range from 0.4 to 0.7.

The microscopic basis for including the nonadiabatic term in Eq. (1) is more controversial. Berger first introduced such a term as a consequence of the Stern–Gerlach force on conduction electrons by the gradient in the *s–d* exchange field [2]. This term may also arise from linear momentum transfer [11], spin-flip scattering [13], or directly from adiabatic STT if Lifshitz-type damping, rather than the Gilbert form, is used [16]. Here we treat it simply as a parameter to be determined by experiment.

2.2. Domain wall structures in nanowire geometries

Given the equation of motion equation (1), the next step is to apply it to a domain wall. A "nanowire" as defined here is a planar ferromagnetic stripe of length L, width w, and thickness t along $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$, respectively, with $L \gg w > t$. The structure of a wall depends on a balance between exchange and anisotropy energies. The former is minimized when spins lie parallel to one another; the latter encourages alignment along a preferred axis. In soft magnetic materials such as Permalloy, shape anisotropy dominates, and domains lie along the wire axis. Walls separating antiparallel domains come in two topologies: transverse and vortex. The transverse wall of Fig. 1(a), in which $\mathbf{m}$ rotates continuously across the wall, efficiently minimizes exchange energy at the expense of free magnetic poles at the edges. The resulting magnetostatic energy grows with w and t. As either of these dimensions increases, the system eventually favors a "closure" structure such as the vortex wall of Fig. 1(b), in which the magnetization circulates in the plane about a small perpendicular "vortex core." This configuration minimizes free poles but increases exchange energy. By comparing the magnetostatic energy of a transverse wall to the additional exchange energy associated with a vortex, McMichael and Donahue [17], and later Nakatani et al. [18], arrived at a phase boundary $w\cdot t \approx 60L_{\mathrm{ex}}^2$ (Fig. 1c), where the exchange length $L_{\mathrm{ex}} \approx 5\,\mathrm{nm}$ for Permalloy. TWs are stable in thin, narrow wires, but VWs are preferred as either dimension is increased. Modern magnetic imaging techniques have provided experimental verification of these wall structures and their relative energies [19].

2.3. Transverse domain walls: the one-dimensional approximation

Transverse domain walls are the simplest to treat analytically, using a one-dimensional wall approximation whose equations of motion are well known [10]. In this model, $\mathbf{m}$ rotates from $-\hat{\mathbf{x}}$ to $+\hat{\mathbf{x}}$ over a characteristic distance Δ, inclined from the easy plane by an angle ψ

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