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Generalized analysis of thermally activated domain-wall motion in Co/Pt multilayers

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ABSTRACT

Thermally activated domain-wall (DW) motion driven by magnetic field and electric current is investigated experimentally in out-of-plane magnetized $Pt(Co/Pt)_3$ multilayers. We directly extract the thermal activation energy barrier for DW motion and observe the dynamic regimes of creep, depinning, and viscous flow. Further analysis reveals that the activation energy must be corrected with a factor dependent on the Curie temperature, and we derive a generalized Arrhenius-like equation governing thermally activated motion. By using this generalized equation, we quantify the efficiency of current-induced spin torque in assisting DW motion. Current produces no effect aside from Joule heating in the multilayer with 7-Å thick Co layers, whereas it generates a finite spin torque on DWs in the multilayer with atomically thin 3-Å Co layers. These findings suggest that conventional spin-transfer torques from in-plane spin-polarized current do not drive DWs in ultrathin Co/Pt multilayers.

1. Introduction

The dynamics of magnetic domain walls (DWs) driven by magnetic field [1–11] or electric current [12–45] is often dictated by interactions with defects. For potential device applications [10–13], it is important to investigate DW dynamics in patterned strips of ferromagnetic thin films, especially materials with perpendicular magnetic anisotropy (PMA) that have shown low critical current densities and high maximum velocities for DW motion [15–22,39,43–45]. DWs in these out-of-plane magnetized thin films are narrow (~1–10 nm wide) and susceptible to pinning by nanoscale defects at sufficiently low driving fields or current densities [1–8,23–30,33–43]. In this case, a DW moves stochastically from one pinning site to another by thermal activation [1,2,46]. Reliable device operation requires a good understanding of such stochastic DW dynamics.

Thermally activated DW dynamics is also interesting from the standpoint of fundamental physics. The dynamics of a DW driven through disorder can exhibit universal scaling behavior spanning several decades in velocity, with scaling exponents that depend on the sample dimensionality [5] and the nature of the driving forces [29,40]. Thermally activated DW motion is typically understood to follow the power law of creep, which relates the thermal activation energy barrier E_A to the effective driving field H_{eff} through a scaling exponent μ. In the case of a one-dimensional elastic DW in a two-dimensional disorder potential, appropriate for ultrathin films with PMA, it has been shown theoretically that $\mu = 1/4$ [2]. This form of creep scaling has been shown, or assumed, to hold in many other experimental studies [2–6,19,26,29,33,34,36] of out-of-plane magnetized ultrathin films, typically evidenced by linearly fitting the logarithm of the DW velocity against $H_{eff}^{-\mu}$. However, a recent investigation [38] of thermally activated DW motion in Co/Pt multilayers with PMA indicates that such an analysis is relatively insensitive to μ, and that significant deviations from universal scaling can become apparent when sample temperature is included as a variable. To elucidate the fundamentals of thermally activated DW dynamics, a rigorous and generalized experimental scheme incorporating temperature dependence is needed.

In general, the velocity of a DW in the thermally activated regime is expressed by the Arrhenius relationship:

$$v = v_o \exp\left(\frac{-E_A}{k_B T}\right), \qquad (1)$$

where k_B is the Boltzmann constant, T is the sample temperature, and v_o is the pre-exponential factor. Because of this exponential relationship, the DW velocity (or depinning rate) is sensitive to even small variations in temperature. Therefore, the DW velocity may increase significantly through Joule heating from driving current [31–33,38], obscuring the contributions from spin torque effects [47–53]. By contrast, the activation energy depends directly on the driving field H and current density J_e, which can be

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considered together as an effective field (e.g. $H_{eff} = H + \epsilon J_e + cJ_e^2 \ldots$) [29,35,54,55]. The efficiencies of spin torques (ϵ, c, etc.) may be extracted by examining the functional dependence of the activation energy barrier on the driving current. This is often performed by analyzing the DW velocity within the framework of a particular creep scaling model. However, E_A can also be extracted directly from Eq. (1) through an Arrhenius analysis [38] from which its dependence on driving forces can be evaluated empirically without assuming a particular model of creep scaling. Despite the significance and utility of the activation energy, there have been few studies to measure it directly as a function of field and current through such a temperature-dependent analysis [38,39].

We present a comprehensive study of field- and current-driven thermally activated DW motion in out-of-plane magnetized Co/Pt multilayers by building on the approach in [38]. From temperature-dependent measurements spanning up to 8 decades in DW velocity, we directly extract the activation energy over a wide range of driving field, from deep in the creep regime up to the viscous flow regime. Further analysis of the activation energy as a function of driving field reveals a nontrivial dependence on the Curie temperature of the sample. By incorporating this newly found temperature contribution, we empirically derive a modified Arrhenius-like relationship that determines the DW velocity as a complete function of driving field and temperature. From this Arrhenius-like relationship and the current dependence of the activation energy, we quantify the effects of current on DW motion as an effective driving field. Our results demonstrate limitations of the universal creep scaling law and the robustness of the direct analysis of the activation energy.

Furthermore, the spin-torque efficiencies for Co/Pt multilayers with different Co layer thicknesses resolve the disparity in recent studies of current-induced DW dynamics in Co/Pt, some reporting high spin-torque efficiencies of over 10 Oe/10^{11} A/m^2 [23,24,26,29,34] while others showing no effects other than Joule heating [19,30–34,38,39]. Our results suggest that the in-plane current through the ultrathin ferromagnetic layers attains a vanishingly small effective spin polarization, consistent with the rigorous semi-classical calculations by Cormier et al. [32] and the recent experimental findings by Tanigawa et al. [16]. In ultrathin Co/Pt-based structures, conventional spin-transfer torques (STTs) are likely not present, and the current-induced torque from the spin Hall effect [56,57] drives DWs as reported in recent studies [42–45,53,58].

2. Experimental details

500-nm wide Co/Pt multilayer strips with electrodes (Fig. 1(a)) were fabricated using e-beam lithography, sputtering, and liftoff. The multilayer structure was Si/SiO$_2$(500)/TaOx(40)/Pt(16)/[Co(t_{Co})/Pt(10)]$_2$/Co(t_{Co})/Pt(16), where numbers in parentheses indicate thicknesses in Å. The Pt layer thicknesses and TaOx underlayer were optimized in an attempt to maximize current flow through the ferromagnetic Co layers while maintaining strong PMA [59]. We present results for t_{Co}=7 Å and 3 Å the upper and lower limits, respectively, at which the remanent magnetization was fully out of plane and the DW nucleation field H_{nuc} exceeded the propagation field. H_{nuc} was ≈230 Oe for t_{Co}=7 Å and ≈35 Oe for t_{Co}=3 Å which set the maximum driving field at which the DW velocity could be measured.

The DW velocity was measured as a function of field, current, and temperature using a high-bandwidth scanning magneto-optical Kerr effect (MOKE) polarimeter. The measurements tracked DW propagation along a 10 – μm strip segment at timescales spanning up to 8 decades, following the procedure described in [7]. For each measurement sequence, a reversed domain was initialized by the Oersted field from a current pulse through the transverse Cu nucleation line (Fig. 1(a)). Then, an out-of-plane driving field H expanded the reversed domain and drove a DW away from nucleation line (left to right in Fig. 1(a)). In some measurements (Section 5), DW motion was assisted by an in-plane DC current J_e injected through the Co/Pt strip. The substrate temperature T was controlled to an accuracy of ±0.2 K with a thermoelectric module.

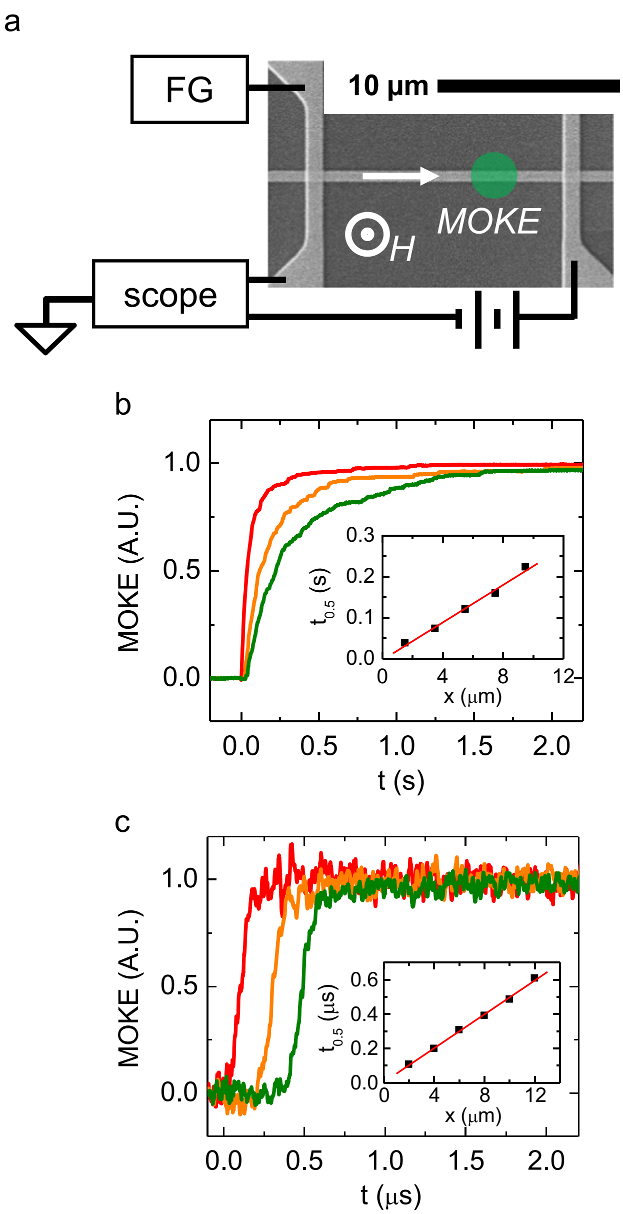

Fig. 1. (a) Scanning electron micrograph and measurement schematic of a Co/Pt sample. (b, c) Examples of averaged MOKE transients for the t_{Co}=7 Å strip at T=300 K and (b) H=123 Oe and (c) H=230 Oe. Individual curves are transients measured at different positions along the Co/Pt strip. The insets show linear fitting for average arrival time $t_{0.5}$ versus probed position.

For each driving parameter set (H, J_e, T), the MOKE transient signal was averaged over at least 100 cycles to account for the stochasticity of thermally activated DW motion. These averaged MOKE transients (Fig. 1(b) and (c)) represent probability distributions for magnetization switching due to DW motion. The insets of Fig. 1(b) and (c) show the average DW arrival time, taken as the time $t_{0.5}$ corresponding to 50% switching probability, plotted against probed position along the strip. The linear increase in $t_{0.5}$ versus position implies a uniform average DW velocity governed