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Dynamics of spin torque switching in all-perpendicular spin valve nanopillars

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ABSTRACT

We present a systematic experimental study of the spin-torque-induced magnetic switching statistics at room temperature, using all-perpendicularly magnetized spin-valves as a model system. Three physical regimes are distinguished: a short-time ballistic limit below a few nanoseconds, where spin-torque dominates the reversal dynamics from a thermal distribution of initial conditions; a long time limit, where the magnetization reversal probability is determined by spin-torque-amplified thermal activation; and a cross-over regime, where the spin-torque and thermal agitation both contribute. For a basic quantitative understanding of the physical processes involved, an analytical macrospin model is presented which contains both spin-torque dynamics and finite temperature effects. The latter was treated rigorously using a Fokker–Plank formalism, and solved numerically for specific sets of parameters relevant to the experiments to determine the switching probability behavior in the short-time and cross-over regimes. This analysis shows that thermal fluctuations during magnetization reversal greatly affect the switching probability over all the time scales studied, even in the short-time limit.

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1. Introduction

Magnetization dynamics of a nanomagnet in the presence of thermal noise is a topic of great fundamental interest and one of importance for magnetic information storage, memory and logic technologies. Moreover, the problem becomes particularly rich when spin-polarized currents are applied to a nanomagnet. These currents lead to spin-transfer torques (STTs) on the magnetization that may drive the nanomagnet out of equilibrium and reverse its magnetization direction [1,2]. In the past ten years there has been a great effort to use this phenomenon and create a magnetic random access memory (MRAM) that would scale with the CMOS technology below 30 nm, known as spin-transfer torque (STT)-MRAM [3].

A model system to study current induced switching is a nanopillar spin-valve with perpendicularly magnetized magnetic layers (hereafter referred to as an all-perpendicular spin-valve). These have two thin magnetic layers separated by a non-magnetic metal layer patterned into a 50–200 nm lateral scale ‘pillar,’ with top and bottom electrical contacts so that current can be passed perpendicular to the layer planes. Both magnetic films have strong magnetic anisotropy perpendicular to the film plane yet different coercive fields, anisotropy constants and/or magnetic moments. The softer magnet is called the ‘free layer,’ whose magnetization reversal is studied when subject to spin-polarized currents. The harder magnetic is called the ‘reference layer’ and is designed to retain a fixed magnetization direction during the free layer switching.

These samples are model systems for the following reasons. First, because the nanomagnets have high spatial symmetry; the dominant magnetic anisotropy is uniaxial. For uniaxial magnetic anisotropy, the equations of motion of the magnetization in the presence of a spin-torque have analytic solutions in the macrospin limit. This also enables analytic solutions for the switching probability even in the presence of thermal noise in certain cases [4–7]. Therefore experimental data on the switching probability of such samples can be compared directly to analytic models. Second, the all-metallic structure enables one to apply large currents (and current densities), far greater than the critical current, enabling high-drive amplitude, short-time scale (sub-nanosecond) switching studies. Finally, the spin-valve giant magneto-resistance (GMR) response can be used to

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detect either the parallel (P) or antiparallel (AP) relative magnetization alignment of the free and reference layer, providing a fast and convenient means to measure the magnetic switching statistics.

Earlier experiments explored the magnetization reversal of thin film nanomagnets with in-plane easy axis incorporated into spin-valves [8–11] as well as magnetic tunnel junctions (MTJs) [12–14]. During the switching process, the magnetization is driven out-of-the-film plane and creates a demagnetization field perpendicular to the film plane, which makes the magnetization trajectory complicated. The development of perpendicular magnetic anisotropy (PMA) materials with high spin-polarization has permitted the realization of all-perpendicular spin-valve nanopillars [15]. The quasistatic field-current state diagrams have been studied [16,17] and a critical current as low as 120 μA has been reported in elements that are thermally stable at room temperature [18], which is of great interest for applications [19,20]. The switching behavior under spin-polarized current pulses has been studied by the authors previously where we determined the switching probability P as a function of the pulse amplitude I and pulse duration τ. We presented the $I-\tau$ boundary for 50% switching probability for AP→P switching with short duration pulses in Ref. [21] and the 50% $I-\tau$ boundary as well as the switching probability distributions for AP→P switching over a broad range of time scales at zero applied field in Ref. [22].

In this paper, we present a comprehensive experimental study along with an extensive theoretical analysis of the switching process with current pulse durations between 50 ps and 1 s for both AP→P and P→AP switching. The data reveals three different regimes that depend on the pulse conditions i.e. a short time–high pulse amplitude regime, a cross-over regime and a long time–low pulse amplitude regime. Both the 50% probability boundary and the probability distributions have totally different forms in these three regimes, suggesting different underlying switching processes.

We analyze our data using a macrospin model based on the LLG equation including the Slonczewski STT term [1] and thermal noise. We use simplifying approximations for the noise to elucidate the basic physics of the three regimes we have found experimentally. In the short time–high pulse amplitude regime we assume that the motion of the magnetization is deterministic but starts from a thermally distributed initial magnetization state. In the long time regime, we consider the switching process as thermally activated reversal over an energy barrier that has been modified by the spin-polarized current. We show that this simple model can explain most of the data quantitatively in both short time and long time regimes. We also show to what extent the theoretical predictions deviate from the experimental results and provide possible explanations.

From this analysis, we are able to obtain important (effective) parameters, such as the energy barrier to reversal U and the critical current I_c, that describe the switching probability over all the time scales mentioned above. For the cross-over regime, we have to consider both thermal fluctuations and the STT as well as the magnetic fields on equal footings. To further understand the thermal effects during the switching process, we present a corresponding Fokker–Planck (FP) calculation which takes into account both the spin-transfer and thermal effects at all times. We show that the forms of the switching probability distributions obtained from both the LLG (no thermal fluctuations during switching) and the FP calculations are the same, yet with different effective parameters. Therefore both models fit the experimental data. However, we find that the zero temperature LLG model greatly underestimates the energy barrier to magnetization reversal.

The outline of the paper is as follows. In Section 2 we introduce the sample structure and the basic switching probability measurements. In Section 3 we present a macrospin LLG model used for analyzing the experimental data in both short time and long time regimes, where analytic solutions are obtained in limiting cases. In Section 4 more detailed experimental data and a comparison of the results to the macrospin LLG theoretical predictions are presented. Section 5 describes a FP model and its comparison to experiment, which suggests the importance of thermal effects during the switching process in virtually all accessible experimental conditions (e.g. when the current amplitude is less than ten times of the critical current).

2. Sample structure and switching probability experiments

2.1. Sample geometry

Experiments were conducted on spin-valves that were patterned into nanopillars combining e-beam and optical lithography. The magnetic layers, a reference and a free layer, both with perpendicular magnetic anisotropy, were separated by a thin Cu spacer. The free layer is a Co/Ni multilayer and has a coercive field of about 100 mT at room temperature. The reference layer is designed to have higher magnetic moment and perpendicular magnetic anisotropy. It has a coercivity of about 1 T. The large coercivity difference between the free and the reference layer makes it possible to choose an external field value that saturates the free layer while keeping the reference layer unchanged. The reference layer consists of a composite of [Co/Pt] and [Co/Ni] multilayers. The layer stack is Ta(5)/Cu(30)/Pt(3)/[Co(0.25)/Pt

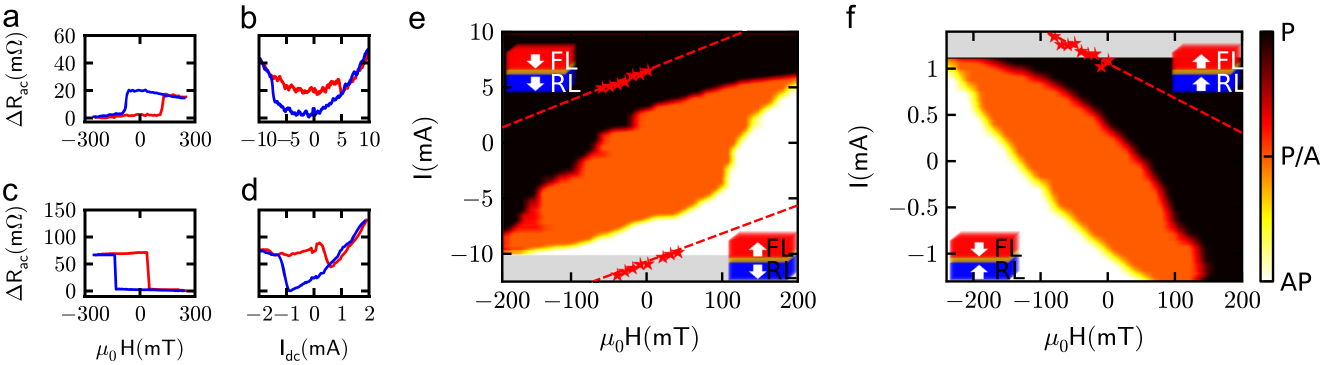

Fig. 1. (a) Hysteresis measurement of the 100 nm × 100 nm spin valve nanopillar. The red curve is data taken when the external magnetic field is increasing and the blue curve for decreasing field. (b) A current sweep measurement of the same sample. The red curve is for the current increasing and the blue curve for the current decreasing. (c) A hysteresis and (d) a current sweep measurement of the 50 nm × 50 nm nanopillar. (e) A state diagram for the 100 nm × 100 nm sample. The black (white) color indicates the P (AP) state, and the red color indicates the region where the sample is stable in both the P and AP states. The red stars are the critical thresholds derived from switching by short time pulses with linear fits indicated by the dashed lines. Similarly, (f) a state diagram for the 50 nm × 50 nm sample with the same color scheme. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

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