Journal of Magnetism and Magnetic Materials 467 (2018) 96–107

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Write error rates of in-plane spin-transfer-torque random access memory calculated from rare-event enhanced micromagnetic simulations

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ARTICLE INFO

Keywords:
Spin-transfer-torque
Write error rate
Micromagnetic simulations
Incoherent switching
Rare-event-enhancement

ABSTRACT

Stochastic magnetization dynamics at non-zero temperatures gives rise to write errors in spin-transfer-torque random access memory (STTRAM). In this paper, the write error rate (WER) of an in-plane STTRAM bit is estimated by extending a previously developed rare-event-enhancement (REE) technique for spin-transfer-torque switching to an in-plane magnet. Reliable calculation of write error rates up to 10^{-9} is demonstrated with only $\sim 10^3$ micromagnetic simulations, thereby making an otherwise prohibitively large computational burden tractable. For the in-plane bit studied here, WERs obtained from the REE-enabled micromagnetic simulations are found to be higher than those obtained within a spatially-coherent (macrospin) switching assumption. Spatially-incoherent switching modes of different types are observed to reduce the switching speed. A detailed study of these spatially-incoherent modes reveals that, at lower applied currents, the end mode controls the WER slope, whereas, at higher applied currents, switching via vortices or anti-vortices governs the WER slope. A sharp change in the WER slope is observed when the latter type of excitation begins to dominate the unswitched population. By further improvements to the REE technique to selectively take into account the vortices and the anti-vortices, reliable prediction of WERs for all ranges of current is demonstrated. The results could help explain prior experimental observations. REE techniques also could be useful for magnetic devices other than STTRAM where rare events remain important and impact device performance.

1. Introduction

Spin-transfer-torque random access memory (STTRAM) offers scalability to smaller technology nodes, high density and high endurance, potentially solving the scaling challenges faced by most of the common semiconductor memories in use, such as dynamic random access memory (DRAM) and static random access memory (SRAM) [1]. STTRAM, thanks to intense attention from the scientific community in the past decade, is already in transition from prototypes to production. In an STTRAM memory bit, the state of the bit is defined by the magnetization direction of a patterned magnet (the so-called “free layer”). However, the magnetization is subject to thermal fluctuations, which leads to finite memory lifetimes and, of specific interest here, which makes the time for the bit to switch from “State 1” to “State 0” and vice versa an intrinsically stochastic quantity [1,2]. If the write current pulse is turned off while the transition of the magnetization direction from one energy minima (say, “State 1”) to the other energy minima (“State 0”) is not yet complete, the magnet could return to the original state (“State 1”) and the write operation fails. Hence, there is a non-zero probability (referred to as the write error rate) that the bit would not be written successfully under any given write current pulse length and duration. For successful use of STTRAM as a stand-alone as well as embedded memory, the write error rate (WER) has to be acceptably low (the value of which possibly would be decided by presence and efficiency of an error correcting circuit) for a low enough write current, so that the energy per write operation is not unacceptably high. Typically, a WER less than at least 10^{-9} would be desired for reasonable energy per write operation [1].

If the free layer is large compared to the exchange length of its material, magnetic moments in it can be spatially-incoherent during switching between energy minima. The spatial incoherence of spins under the combined influence of spin-transfer-torque (STT) from the write current and the thermal fluctuation can be modeled by integration of the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation, with input of a stochastic thermal field, using micromagnetics. Due to the large computational load posed by stochastic micromagnetic simulations and the requirement of $\gg 10^9$ conventional stochastic simulations to predict a WER of 10^{-9}, magnetization dynamics of the free layer is

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https://doi.org/10.1016/j.jmmm.2018.07.042
Received 26 February 2018; Received in revised form 24 May 2018; Accepted 11 July 2018

most commonly modeled by ignoring the spatial incoherence and approximating the magnetization direction as a single (time varying) vector, the so-called macrospin approximation [2–4]. However, the macrospin approximation fails to model many experimentally observed effects, such as those caused by higher order spin wave modes [5], switching via non-uniform magnetization states [6,7], sub-volume excitations [8] and branching of WER with increasing write voltage/current, and larger WER than otherwise expected from macrospin physics [9–12]. Hence, accurate physical understanding of these effects would require full micromagnetic simulation under the effect of both STT and thermal fluctuations.

In previous studies, up to 10^3 independent micromagnetic simulations were employed to investigate such spatially-incoherent processes and estimate switching probabilities [13–18]. However, extreme tails of WERs are beyond the scope of such simulations. In previous work, we demonstrated reliable estimation of WERs up to 10^{-9} using only $\sim 10^3$ micromagnetic LLGS simulations for a perpendicular STTRAM (P-STT) bit by employing a "rare-event-enhancement" (REE) technique [19] using a predictor of rare events based on the perpendicular component of the magnetization. In this work, we first extend this technique to an in-plane STTRAM (I-STT) bit using a predictor of rare events based on the easy-axis magnetization and, to address the oscillatory nature of the switching process for I-STT, time averaging over the natural oscillation period for the hard-axis component of the magnetization. This REE technique allows us to investigate the tails of the WER with increasing switching time, and, thereby, investigate the physical reasons behind the extremely slow switching without incurring a prohibitively large computational expense. Our study finds that, among other things, the extremely slow cases of switching can become dominated by certain types of spatial incoherence in the magnetization, such as the vortex (V) and anti-vortex (AV) states. Moreover, once these latter states become dominant, they lead to a reduced slope (magnitude) of the WER vs switching time curve, i.e., a "branching" in the WER characteristic. These V and AV states, however, not only cannot be captured by macrospin models, of course, but also become problematic to follow to much smaller WERs for the as so-far modified REE-enhanced Monte Carlo micromagnetic simulations. Therefore, we further modified the REE method by adding a new predictor of rare events to selectively address these vortices and anti-vortices based on what is called the "topological charge" or "skyrmion number" which then allows for reliable REE-enhanced prediction of WERs to the lowest considered values of 10^{-9} for all considered currents.

This paper is organized as follows: In Section II, we begin by providing a brief overview of the REE Monte Carlo technique developed in our previous study [19]. We then discuss basic modifications necessary for applying this technique to I-STT bits and illustrate the validity of the resulting REE method by comparison to non-REE macrospin simulations within WER range allowed by the latter. In Section III, we show the WER for I-STT predicted from REE-enabled micromagnetic simulations, including branching of the WER vs. time slope at low WERs. In Section IV, we characterize the spatially incoherent end mode, vortex and anti-vortex magnetization distributions in the free layer that lead to the branching of the WER curve and associated extremely long switching times. We then describe the further modification of the REE method via a"topological charge"-based predictor of rare events to also allow reliable REE-enabled prediction of WERs in the presence of these states to the lowest considered values of 10^{-9} for all considered currents. We then conclude this article in Section V.

2. Initial modifications of the REE technique for I-STT bits

2.1. Details of the simulated bit

Fig. 1(a) shows a magnetic tunnel junction with a free layer (FL) magnet and a reference layer (RL) magnet patterned in an elliptic shape, as used for an I-STT bit. Switching from the parallel state to the anti-parallel state is considered. Only the FL is included in our simulations assuming the RL acts only as a source of spin-polarized current that flows along the surface-normal direction (z-axis) of the free layer. The FL is assumed to have a major axis of 150 nm along the x-axis, a minor axis of 50 nm along the y-axis and a thickness of 2 nm along the z-axis. A saturation magnetization $M_s = 0.8 \times 10^6$ A/m and a Gilbert damping constant $\alpha = 0.01$ were used. The spin-polarization direction of the current (from the reference layer) is along $+x$ with a polarization factor $\eta = 0.4$. Field-like torque has not been considered. Assuming a rectangle of the same lateral dimensions, demagnetization factors of the FL magnet are estimated to be $N_{xx} = 0.0181$, $N_{yy} = 0.0562$ and $N_{zz} = 0.9257$ [20]. The demagnetizing factors of the elliptic FL magnet also could be obtained by approximating it as a thin cylindrical disk [21] or as a very flat ellipsoid [22,23]. We have verified that the macrospin WER remained essentially the same with any of the above choices for the demagnetizing factors. The thermal stability factor Δ of the I-STT bit is given by $\Delta = \frac{1}{2}\mu_0 V M_s^2 (N_{yy} - N_{xx})/k_B T$, where V is the volume of the bit, k_B is the Boltzmann's constant, μ_0 is the vacuum permeability. Within the macrospin approximation, the critical current I_{c0} for STT switching can be written as, $I_{c0} = \frac{\alpha}{\eta\hbar} q\mu_0 V M_s^2 (N_{yy} + N_{zz} - 2N_{xx})$, where, q is the (magnitude) of electron charge and $\hbar$ is the reduced Planck's constant. With the above set of material parameters and dimensions, $\Delta = 43.7$ and $I_{c0} = 0.34$ mA. Temperature is set to $T = 300$ K for all simulations. All the simulation parameters are summarized in Table 1. Material parameters used here are typical of magnetic tunnel junctions with CoFeB electrodes and MgO tunnel barrier as mentioned in [4]. Following Brown's prescription [24], a thermal fluctuation field was added to the LLGS equation for all the simulations included in this paper. The stochastic LLGS equation is then integrated with a time step of 0.1 ps using the scheme of Heun [25] for all the macrospin simulations. Initial ($t = 0$) equilibrium thermal distributions of $\overrightarrow{m}(t)$ are obtained by starting with $m_x = 1$ and integrating the stochastic LLGS equation for 5 ns without STT.

2.2. REE method

The REE method developed in our earlier work is based on the technique of "importance splitting" [26,27]. The basic idea is that rare extremely slow trajectories can be reached with high probability by repeatedly splitting selected "parent" trajectories into multiple "offspring" trajectories while reducing their weight accordingly. The first requirement is to choose a predictor of which trajectories, $\overrightarrow{m}(t)$, are more likely to lead to rare events than others. For a P-STT bit, the state of the bit is well characterized by the surface-normal component of magnetization unit vector, m_z, and hence m_z was used as the predictor to identify rare trials. Similarly, for an I-STT bit, we choose m_x, the component of magnetization unit vector along the in-plane easy axis, as the predictor. Due to the axial symmetry of a circular P-STT bit, m_z varies monotonically (except small fluctuations due to random thermal field) from the initial state ($m_z \approx +1$) toward the final state ($m_z \approx -1$) during switching. In case of an elliptic I-STT bit, m_x switches from the initial state ($m_x \approx +1$) to the final state ($m_x \approx -1$) via large pre-switching oscillations, as shown by the grey trajectories in Fig. 1(b). At any time, t, the state of the trajectory may not be obvious from the instantaneous value of the predictor m_x. To substantially resolve this issue, m_x is filtered via a moving average over a time window (τ_w). τ_w is taken as the oscillation period of the strongest frequency component present in the pre-switching small-amplitude oscillations of m_y, the component of magnetization along the in-plane hard axis. Within the macrospin approximation, e.g., this frequency is found to be the same as the frequency of the uniform mode given by Kittel's formula [28]. As shown in Fig. 1(b) (blue trajectories), pre-switching oscillations are strongly suppressed in the time averaged trajectories, $\underline{m}_x$, making it suitable for use as a predictor. The suppression is not perfect because