THERMAL STABILITY DETERMINATION BY CURRENT-DRIVEN SWITCHING: LIMITATIONS OF MACROSPIN MODEL

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I. INTRODUCTION

In the last few years, there was a lot of controversy regarding one of the fundamental properties of the perpendicular STT-MRAM: thermal stability of the free layer. The two standard measurements of thermal stability of a single MRAM cell rely on accelerating the switching rate by either application of the magnetic field (field-driven switching) or current (current-driven switching) of various amplitude and study of switching rate as a function of the amplitude of the field (or current) and subsequent application of macrospin-based model to extract the value of thermal stability. These measurements result in thermal stability, which is almost constant as a function of diameter above 30-40 nm [1,2] in contrast to expected increase of Δ (e.g. as demonstrated by NEB (Nudged Elastic Band) modeling)[3]. A lot of effort was spent on solving this paradox, mostly focusing on modification of the underlying model (e.g. “effective nucleation volume” picture). An important discovery was chip measurements at elevated temperatures without application of magnetic field or current that showed *Δ* increasing with size for all studied dimensions [4]. The same study also demonstrated that application of the field to accelerate the switching results in flat dependence of delta on the size, which was associated with artifact coming from using the macrospin model to describe non-macrospin behavior [4]. In our work, we evaluate the behavior of thermal stability obtained by current-driven switching using either quadratic or linear anzats [5] and compare the results to Δ obtained by Nudged Elastic Band (NEB) modeling[3] and discuss the limitations of the macrospin model.

Subject: TMRC 2018 – Digest

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II. DELTA DEPENDENCE ON THE CURRENT

For in-plane STT-MRAM structures, it was shown that the switching current at long pulses depends in the following way on the pulse width t_p and Δ [6]:

$$J_c(t_p) = J_{c0}\left(1 - \frac{1}{\Delta} ln(t_p f_0)\right) \quad (1)$$

This equation was used as a standard way to extract both Δ and the critical switching current density J_{c0} for in-plane structures by measuring J_c (t_p) at t_p >> 1 ns. It was inferred that this equation also holds for perpendicular free layer and is still used by many research groups. In our previous work [5], we used brute-force macrospin modeling and showed that the above approach would give underestimation of both Δ and J_{c0} and instead the following dependence should be used [5]:

$$J_c(t_p) = J_{c0}\left(1 - \frac{1}{\sqrt{\Delta}}\sqrt{ln(t_p f_0)}\right) \quad (2)$$

which should give the correct Δ and J_{c0}. This was in agreement with prior theoretical work by others [7,8,9]. The above formula still assumes the free layer to behave as a single moment (macrospin assumption). In this work, we perform micromagnetic modeling to evaluate the limitations of the above approach and discuss some of the important implications of non-homogeneity of spin-torque driven switching.

III. MICROMAGNETIC MODELING

We used GPU-based micromagnetic code (not macrospin) to simulate a thermally-driven switching of a single MTJ cell as a function of the applied current. To speed-up the simulation, only the free layer is

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modeled. The system is relaxed (at room temperature without the current) for 20 ns and then rectangular current pulse is applied of various pulse width, followed by relaxation for 20 more ns. The probability of the switching is calculated by repeating the simulation a number of times and counting the number of times the free layer has switched. Then, we used the above eq. (1) and (2) to obtain Δ_1 and Δ_2 respectively.

To get thermal stability factor Δ_{NEB} by other means we used Nudged Elastic Band (NEB) method to get the minimum energy barrier connecting two equilibrium states. This method is based on connecting the two states with a series of images of magnetization states and moving the images while preserving the equal distance between them along the local energy gradient to find the switching trajectory that has the smallest energy barrier. This energy barrier should properly account for any non-homogeneity during thermally-activated switching. We found that for typical parameters (A_{ex} = 1 erg/cm, M_S = 1000-1200 emu/cc, thickness between 1.0 and 2.0 nm), the free layer switches by domain wall propagation and the energy barrier varies roughly proportional to the diameter of the cell. When the diameter becomes smaller than 10-15 nm, quasi-uniform rotation becomes the primary switching mechanism since formation of the domain wall at these sizes is no longer energetically favorable.

Then, we will compare Δ_1 and Δ_2 to the Δ_{NEB} and discuss the impact of the findings and important artifacts related to macrospin assumption used in eq. (1) and (2).

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