Physics Letters A ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Domain wall nucleation and propagation in spin-transfer torque switching with thermal effects

Bingjin Chen [a,*], Tiejun Zhou [b,*], Siang Yee Sim [a,c], Sze Ter Lim [a], Hao Gong [c]

[a] Institute of Materials Research and Engineering, A*STAR (Agency for Science, Technology and Research), 2 Fusionopolis Way, #08-03 Innovis, 138634, Singapore
[b] Center for Integrated Spintronic Devices, College of Electronics and Information, Hangzhou Dianzi University, Hangzhou, Zhejiang, 310018, PR China
[c] Department of Materials Science & Engineering, National University of Singapore, 21 Lower Kent Ridge Road, 119077, Singapore

A R T I C L E I N F O

Article history:
Received 3 July 2018
Received in revised form 20 September 2018
Accepted 29 September 2018
Available online xxxx
Communicated by M. Wu

Keywords:
Spin transfer torque switching
Domain wall nucleation and propagation
Switching times
Micro-magnetics
Thermal fluctuation

A B S T R A C T

We conduct micro-magnetic simulations to study spin-transfer torque induced magnetization switching in perpendicular magnetic tunneling junctions. The effects of current densities and temperatures on the switching processes are studied in details. We then proposed an approach to compute the deterministic switching time by taking thermal-effect into account. The switching time is less temperature-dependent under higher current density; however, as the current density decreases, the effect of temperature on the switching time becomes more and more significant. The switching process with micro-magnetic simulations is shown to be via domain wall nucleation and propagation. The phenomena are consistent with the recent experimental found-out. We further propose a method to compute the switching time based on domain wall nucleation and propagation theory, and compare the switching time with those from macro-spin approximation. It is found the switching times from the micro-magnetic simulations are much shorter than that from the macro-spin approximations. Macro-spin approximation over-estimates the switching times due to its coherent rotation assumptions.

1. Introduction

Spin-transfer torque magnetic random access memory (STT-MRAM) is one of the promising candidates for on-chip memory technology due to its fast access time, unlimited programming endurance with zero standby power [1–7]. A magnetic tunneling junction (MTJ), the basic component of the STT-MRAM, consists of a three-layer-structure: a free layer (FL), a reference layer (RL), and a thin tunneling dielectric film (MgO) between them. [8–13]. The MTJ resistance is determined by the relative magnetization directions of FL and RL. The MTJ is in high resistance state when the magnetization directions are anti-parallel, and is in low resistance state when the magnetization directions are parallel.

Usually, the switching characteristics of STT-MRAM can be modeled by using macro-spin approximations [14–17] where the magnetization in the free layer is assumed to be in a single-domain mode and move coherently, governed by the Landau–Lifshitz–Gilbert (LLG) equations. Experimentally, however, the STT-induced magnetization switching may exhibit richer features, such as the nucleation and propagation of domain wall, which is non-uniform reversal in nature [18,19]. It is therefore of interest to study the more realistic switching process beyond the macro-spin approximations. Devolder et al. [20] reported time-resolved measurements of STT switching events in perpendicular magnetic tunneling junctions (pMTJ). The magnetization reversal was found to be a complex dynamical non-uniform process with the nucleation and motion of a domain wall.

In this paper, we conduct micromagnetic simulations, including temperature effect, to study spin-transfer torque induced magnetization switching in pMTJ. We proposed a method to determine the switching time by taking temperature-effect into account. The switching time as a function of the current density flowing through magnetic tunnel junction is established. The result is compared with that from the macro-spin approximation, showing clear difference between micromagnetic simulation and the single-domain approximation.

2. Simulation method

As shown in Fig. 1, a perpendicular MTJ has three elements: free layer (FL), reference layer (RL) and tunnel barrier (MgO). The magnetization of the magnetic layers is assumed to be perpendicular to the plane. The switching process of the system can be described by the change of the FL magnetization direction since

* Corresponding authors.
E-mail addresses: Chen_BingJin@imre.a-star.edu.sg (B. Chen), tjzhou@hdu.edu.cn (T. Zhou).

https://doi.org/10.1016/j.physleta.2018.09.041

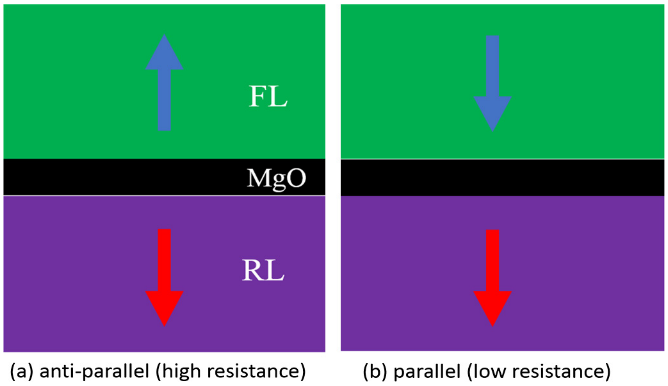

Fig. 1. MTJ structure: (a) anti-parallel (high resistance), and (b) parallel (low resistance).

the magnetization direction of the RL is fixed. We assume that the magnetization in FL is $\boldsymbol{M}$, the dynamics of $\boldsymbol{M}$ satisfies the LLG equation with the Slonczewski torque,

$$\frac{d\vec{M}}{dt} = -\gamma\mu_0(\vec{M}\times\vec{H}_{eff}) + \frac{\alpha}{M_s}\left(\vec{M}\times\frac{d\vec{M}}{dt}\right) + \gamma\mu_0\frac{a_J}{M_s}\vec{M}\times(\vec{M}\times\vec{m}_p) \quad (1)$$

where

$$\vec{H}_{eff} = H_k m_z\vec{z} + \vec{H}_d + \vec{H}_a + \vec{H}_e. \quad (2)$$

Here m_p is a unit vector along the spin polarization direction; γ is the gyromagnetic ratio, α is the damping constant, H_k is the intrinsic uniaxial perpendicular anisotropy field; H_d is the demagnetization field; H_a is the applied Zeeman field, and H_e is the exchange field. a_J is defined as

$$a_J = \frac{\hbar g(\theta)J}{2et\mu_0 M_s}, \qquad g(\theta) = \frac{P}{2(1+P^2\cos(\theta))}, \quad (3)$$

where P is the spin polarization, and θ is the angle between the direction of FL magnetization and the z-axis. Ms is the saturation magnetization, and t is the FL thickness. Thermal fluctuation is taken into account by adding a Langevin random field

$$H_{L,i} = \sqrt{\frac{2\alpha k_B T}{\gamma M_s V}}X_i(t), \quad i = x, y, z \quad (4)$$

Here $X_i(t)$ is a Gaussian random noise with zero mean and unit variance in x, y, and z axis.

The parameters used for the simulations are as follows: exchange constant $A = 2\times10^{-11}$ J/m, saturation magnetization $M_s = 1000\times10^3$ A/m, the FL perpendicular anisotropy field $H_K = 1.6\times10^6$ A/m, and the damping constant $\alpha = 0.01$. The FL size is assumed to be 50 nm × 50 nm × 2 nm, and the discretized cell size is 2 nm × 2 nm × 2 nm. Only the FL is modeled and the simulation is carried out using the Object Oriented Micro-Magnetic Framework (OOMMF) [21] software package.

3. Results and discussion

We first study the thermal effects on the switching processes for different current densities. Plots from Fig. 2a to Fig. 2e illustrate the average m_z (perpendicular magnetization component) of 50 simulations as a function of time at 5 different temperatures for various current densities. The current density is decreased continuously from Fig. 2a to Fig. 2e. It shows that (i) at high current density, switching curves at all temperatures are continuous and smooth (Fig. 2a); (ii) as the current density reduces, the distortion and the fluctuation in the switching curves takes place (Fig. 2b);

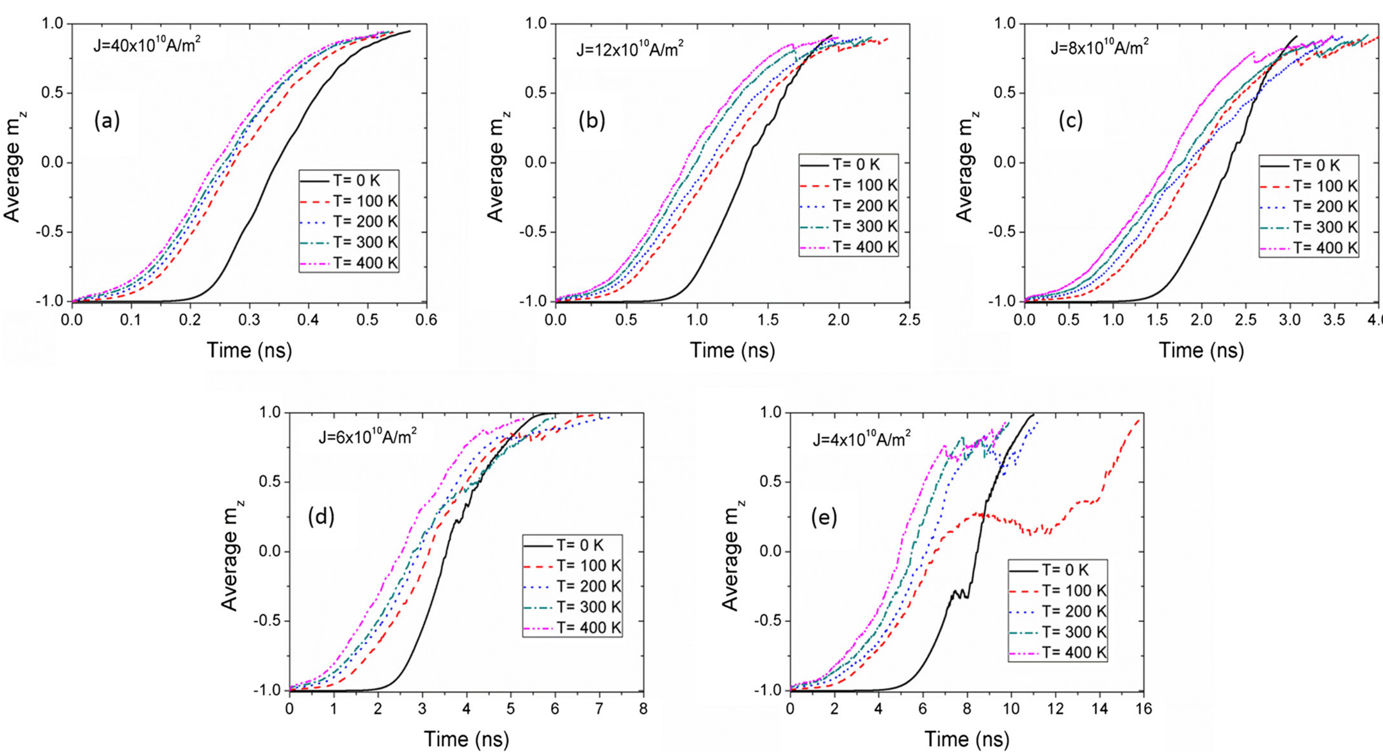

Fig. 2. Average perpendicular magnetization component m_z for 50 simulations against time at different temperatures. The current density is decreased continuously from Fig. 2a to Fig. 2e.

Please cite this article in press as: B. Chen et al., Domain wall nucleation and propagation in spin-transfer torque switching with thermal effects, Phys. Lett. A (2018), https://doi.org/10.1016/j.physleta.2018.09.041