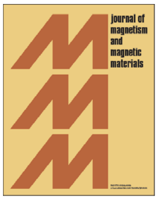
Journal of Magnetism and Magnetic Materials ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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



Modeling of switching energy of magnetic tunnel junction devices with tilted magnetization

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ARTICLE INFO

Article history:
Received 30 January 2013
Received in revised form
9 December 2014
Accepted 18 December 2014

Keywords:
Magnetic tunnel junction
Spin transfer torque
Switching models
Switching energy

ABSTRACT

For spin transfer torque (STT), the switching energy and thermal stability of magnetic tunnel junctions (MTJ) bits utilized in memory devices are important factors that have to be considered simultaneously. In this article, we examined the minimum energy for STT induced magnetization switching in MTJ devices for different in-plane angles of the magnetization in the free layer and the pinned layer with respect to the major axis of the elliptical cylinder of the cell. Simulations were performed by comparing the analytical solution with macrospin and full micromagnetic calculations. The results show good agreement of the switching energy calculated by using the three approaches for different initial angles of the magnetization of the free layer. Also, the low-energy location specifies the suitable value of both time and current in order to reduce the heat effect during the switching process.

1. Introduction

Spin transfer torque (STT) is a novel physical phenomenon which can be utilized to switch the magnetization in nanomagnets [1,2]. It is also a promising mechanism to achieve STT random access memory (STT-RAM) based on magnetic tunnel junctions (MTJ) [3–8]. STT-RAM is currently a popular possible future memory technology because of its distinct advantages, such as high write/read speed, durability, nonvolatility, high recording density, and energy-efficient writing [5,7,9–12]. The MTJ structure consists of the three main components: an insulating barrier layer separating two thin ferromagnetic layers – the free and pinned layers [7,8,11,12]. The magnetization direction in the free layer of the MTJ storage element can be reversed by passing a spin polarized current through the junction [1–3,7,8,12]. The difference in resistance between parallel and anti-parallel orientations of the magnetizations in the two ferromagnetic layers of the MTJ cell is utilized to read out the bit information in STT-RAM [7,8,11,12]. The efficiency of the write/read process increases with increasing tunneling magnetoresistance (TMR) ratio [10,12–15]. Hence MTJ devices with MgO barriers are widely used in STT-RAM because of the high TMR ratio achievable [8,12].

The magnetization dynamics and STT switching can be investigated using a macrospin model or full micromagnetic simulations, based on the Landau–Lifshitz–Gilbert (LLG) equation of motion including the STT term [16]. The macrospin model assumes a homogenous (single-domain) magnetization state, whereas the full micromagnetic model allows for inhomogenous magnetization reversal. The validity of the macrospin approximation is limited to small devices and the upper bound for the critical length scale for single domain behavior can be estimated to be of the order of several tens of nanometers for typical ferromagnets [16]. In 2000, Sun [17] investigated the macrospin dynamics and derived an analytic solution for the STT switching process. His work is extensively mentioned in current research for estimating the critical current for STT induced magnetization reversal in MTJ cells [3,16,18].

Numerous theoretical and experimental studies are focusing on separate aspects to optimize the MTJ regarding the thermal stability, the critical current density, or the switching mechanism itself [4]. It is well known that the phenomenon of spin polarized current induced magnetization switching in the free layer of a MTJ cell can be observed at a current density of the order of several MA/cm^2 [9,10,12,19]. Such a large current density is accompanied with unavoidable Joule heating [9,10,19]. Consequently, the thermal stability of the MTJ cell is reduced during the current injection

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http://dx.doi.org/10.1016/j.jmmm.2014.12.055
0304-8853/© 2014 Published by Elsevier B.V.

Please cite this article as: C. Surawanitkun, et al., Journal of Magnetism and Magnetic Materials (2014), http://dx.doi.org/10.1016/j.jmmm.2014.12.055

[4,5,9]. For device design, achieving a low switching energy is a significant factor that influences the appropriate values of time and current to obtain reliable switching [4,5,20,21]. Recently, there has been a growing interest in the effects of initial magnetization direction in both ferromagnetic layers to reduce the switching current and increase writing speed and to improve the efficiency of spin torque switching in STT-RAM [24–26]. In the present work, we focus on the comparison of the switching energy for STT switching with a tilted magnetization in a single MTJ bit by using Sun's analytical solution, numerical macrospin simulations and full micromagnetic simulations. We also investigate the case of an in-plane tilt of the pinned layer magnetization, which enables a more meaningful comparison between the macrospin model and full micromagnetic simulations.

2. Model and calculation

The energy of spin polarized current-driven switching in MTJ devices was calculated within a three dimensional finite difference method using the Matlab based micromagnetic code M^3 [27]. The switching energy, E_{SW}, in this work is calculated using

$$E_{SW} = I_C^2 \tau_{SW} R_{MTJ}, \tag{1}$$

where I_C, τ_{SW}, and R_{MTJ} are the current, switching time, and the (average) MTJ resistance, respectively. Numerical simulation results are reported here in comparison with the analytic solution, macrospin and full micromagnetic simulations without calculation of thermal fluctuations. The analytic solution for the estimation of τ_{SW} is described by [17]

$$\tau_{SW} = \frac{\tau_0 \ln(\pi/(2\theta_F))}{(I_C/I_{C0}) - 1}, \tag{2}$$

where θ_F is initial angle between the magnetization vector and the major axis in the free layer. The critical current, I_{C0}, and the relaxation time, τ_0, are given as

$$I_{C0} = \frac{2e\alpha\mu_0 M_S V H_{eff}}{\eta P \hbar}, \tag{3}$$

$$\tau_0 = \frac{1+\alpha^2}{\alpha\gamma H_{eff}}, \tag{4}$$

where e is the electron charge, α is the damping parameter, M_S is the saturation magnetization, V is the volume of the free layer, H_{eff} is the effective field, $\hbar = h/(2\pi)$, h is Planck's constant, η is the spin torque efficiency and P is the spin polarizing factor of the free layer. The macrospin and full micromagnetic calculations are based on the LLG equation including the STT term given by [6]

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{eff} - \frac{\alpha\gamma}{M_S} \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{H}_{eff}) - \frac{a_j \gamma}{M_S} \cdot \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{m}_p), \tag{5}$$

where $\boldsymbol{M}$ is the magnetization vector. $\boldsymbol{M}$ and $\boldsymbol{H}_{eff}$ are functions of space and time. $\boldsymbol{H}_{eff}$ includes exchange, anisotropy, demagnetization, and external fields. γ is the gyromagnetic ratio. Regarding the STT term, $\boldsymbol{m}_p$ is a unit vector along the electron polarization direction, a_j is the spin torque factor given as follows:

$$a_j = \frac{\hbar g(\theta) J}{2e\mu_0 M_S t_{free}}, \tag{6}$$

where J is the current density, t_{free} is the free layer thickness, and $g(\theta)$ is a scalar function in Slonczewski's model for GMR devices given by [1,16]

$$g(\theta) = \frac{P/2}{\cos^2(\theta/2) + (1/(1+\chi_a))\sin^2(\theta/2)}, \tag{7}$$

where θ is the angle between the pinned and free layer magnetization and χ_a is the asymmetry parameter. In the following we set the asymmetry parameter $\chi_a = 0$, i.e. we neglect any angular dependence of a_j.

The MTJ cell is assumed to be an elliptic cylinder with a major axis of 130 nm, a minor axis of 50 nm and a free layer thickness of 1.8 nm [4]. The parameters used for the simulation are based on CoFeB thin film properties [28,29]. In particular we use M_s of 8.6×10^5 A/m, α of 0.01, and an exchange stiffness constant, A, of 1.05×10^{-11} J/m. In this work, we are interested to study the energy to switch the magnetization of the free layer with various initial in-plane angles of both free and pinned magnetizations by using a spin polarized current with no external field. Switching was investigated for magnetization reversal from the parallel state to the anti-parallel.

3. Results and discussions

Firstly, the switching effects as the result of the tilted magnetization in the free layer out of the major axis are considered. The switching time, τ_{SW}, is defined as the time period between turning on the current and when the magnetization crosses the in-plane hard axis (minor axis). Fig. 1 shows the τ_{SW} as a function of I_C/I_{C0} for different initial in-plane angles θ_F between the magnetization vector of the free layer and the major axis. As expected, the switching time increases with decreasing I_C/I_{C0} and as the current approaches the critical current $I_C/I_{C0} \to 1$, the switching time $\tau_{SW} \to \infty$, as expected from Eq. (2).

To explore the minimum switching energy, the results are reported with the normalized current I_C/I_{C0} levels. This is because the critical current I_{C0} is based on the physical and magnetic properties and the applied current I_C is an important factor for considering the heat energy. Therefore, in switching process, the reported results are independent of the structural details and can indicate the effect of the applied current with the temperature increment to a minimum. Fig. 2 illustrates the switching energy, E_{SW}, per MTJ resistance, R_{MTJ}, (E_{SW}/R_{MTJ}) as a function of the normalized current I_C/I_{C0} for different initial angles θ_F. The E_{SW}/R_{MTJ} decreases with increasing θ_F due to the reduction of the switching time when starting further away from the easy axis. Based on the analytical model a minimum switching energy as a function of I_C/I_{C0} is expected at $I_C/I_{C0}=2$, which agrees with the numerical simulation results for the macrospin and micromagnetic calculations as shown in Fig. 2. The corresponding minimal switching energy $E_{SW,min}$ is

$$E_{SW,\,min} = 4 I_{C0}^2 R_{MTJ} \tau_0 \ln\left(\frac{\pi}{2\theta_F}\right). \tag{8}$$

Thus, the minimal switching energy is proportional to R_{MTJ}, τ_0, the square of I_{C0} and the natural logarithm of the reciprocal of the initial angle θ_F. Even though differences in the initial conditions lead to a change in the value of the minimal switching energy, its location remains at I_C/I_{C0} of 2; this location is also independent of the details of the structure. This can be seen in Fig. 3 for different structures which have different intrinsic critical currents. The $E_{SW,min}$ of a smaller MTJ cell is lower because of its lower I_{C0} [3,30], which is a well-known advantage of STT switched RAM to other approaches [15]. Additionally, Figs. 1 and 2 also show good agreement of the overall behavior of the switching time and switching energy computed using the analytic solution, the macrospin simulations and the full micromagnetic model. Therefore, the analytic model can be utilized to estimate the switching

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