MODELING OF THE ADVANCED SPIN TRANSFER TORQUE MEMORY: MACRO- AND MICROMAGNETIC SIMULATIONS

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ABSTRACT

We study the dynamics of the switching process in a magnetic tunnel junction composed of 5 layers with the magnetization of the two side layers fixed. The magnetization of the middle free layer can be switched between the two stable configurations by passing the current through the tunnel junction in a certain direction. The dependence of the switching time on the parameters of the penta-layer structure is analyzed.

INTRODUCTION

Memory cells based on electric charge storage, such as flash memory, are rapidly approaching the physical limits of scalability. The increasing demand for minimization of microelectronic devices (e.g., MP3 players and mobile phones) stimulates a significant acceleration in exploring the new concepts for nonvolatile memory. Apart from good scalability, a new memory type must also exhibit low operating voltages, low power consumption, high operation speed, long retention time, high endurance, and a simple structure. (Kryder et al. 2009)
Several concepts were recently proposed and developed for potential replacement of the charge based memory. Some of the proposals are available as prototypes, such as carbon nanotube RAM (CNRAM) and copper bridge RAM (CBRAM), others already as products, e.g., phase change RAM (PCRAM), magnetoresistive RAM (MRAM), and ferroelectric RAM (FRAM), while the technologies based on spin torque transfer RAM, racetrack memory (RTRAM), and resistive RAM (RRAM) are under intensive research.
The theoretical predictions (Slonczewski 1996; Slonczewski 2005) and the experiments (Braganca et al. 2005; Iwayama et al. 2008; Meng et al. 2006; Fuchs et al. 2005; Devolder et al, 2005) of spin transfer switching demonstrated that the spin transfer torque random access memory (STTRAM) is one of the promising can-

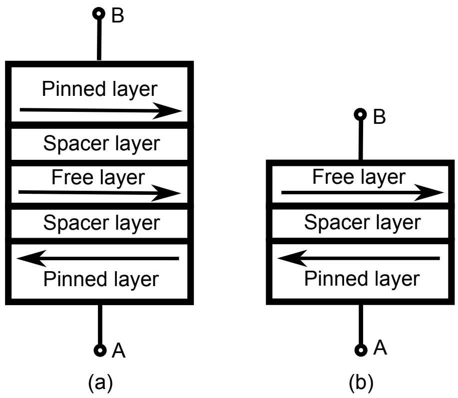


Figure 1: Schematic illustration different MTJ types: (a) penta-layer MTJ; (b) three-layer MTJ.

didates for future universal memory. STTRAM is characterized by small cell size ($4F^2$), fast access time (less than $10ns$), high endurance (10^{16}), and long retention time.
The basic element of the STTRAM is a magnetic tunnel junction (MTJ). The three-layer MTJ (Fig.1b) represents a sandwich of two magnetic layers separated by a thin insulating spacer which forms a tunnel barrier. While magnetization of the pinned layer is fixed during the fabrication process, the magnetization direction of the free layer can be switched between the two states parallel and anti-parallel to the fixed magnetization direction. Switching between the two states occurs due to spin-polarized current flowing through the MTJ.
The spin-polarized current is only a fraction of the total charge current. Therefore high current densities are required to switch the magnetization direction of the free layer. The reduction of the current density required for switching and the increase of the switching speed are the most important challenges in STTRAM research. Several strategies have been proposed to decrease the switching time below a few nanoseconds: by pre-charging with a bias current (Devolder et al. 2005), by combining a spin-polarized current together with a small radio frequency field (Finocchio, Krivorotov, et al.

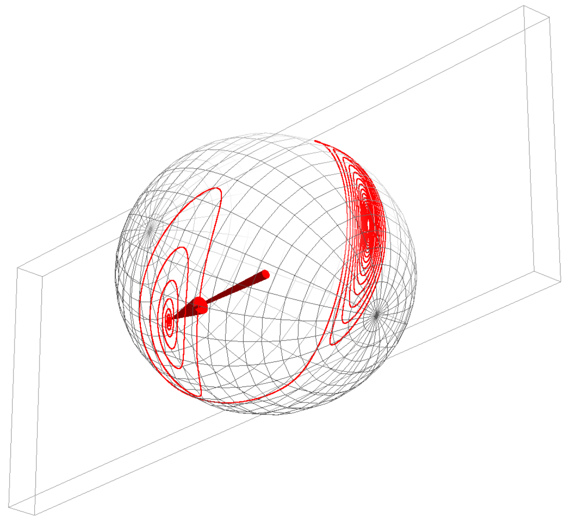
2006), and by applying a magnetic field perpendicular to the magnetization direction (Devolder et al. 2006).

Measurements performed by (Fuchs et al. 2005) showed a decrease in the critical current density for the penta-layer magnetic tunnel junction shown in Fig.1a. The structure represents a magnetic tunnel junction composed of 5 layers, with the magnetization of the two side layers fixed. The spin torque enhancement in penta-layer structures results in a significantly lower critical switching current at a switching delay comparable to that in three-layer structures, which makes the penta-layer cells attractive for low power high performance memory applications. In this work we briefly describe an implementation of a penta-layer model in our micromagnetic simulation environment. It allows us to investigate the dynamics of the switching process in a penta-layer MTJ. Such a penta-layer structure was recently analyzed (Mojumdar et al. 2010) by using the ballistic Green's function formalism combined with the soft magnetic layer dynamics based on the Landau-Lifshitz-Gilbert equation. The spin torque enhancement was found in the anti-parallel penta-layers (the magnetizations of the two fixed layers are anti-parallel) as compared to the three-layer structure. This enhancement manifests itself only under the dual barrier resonance tunneling conditions, when the current is high.

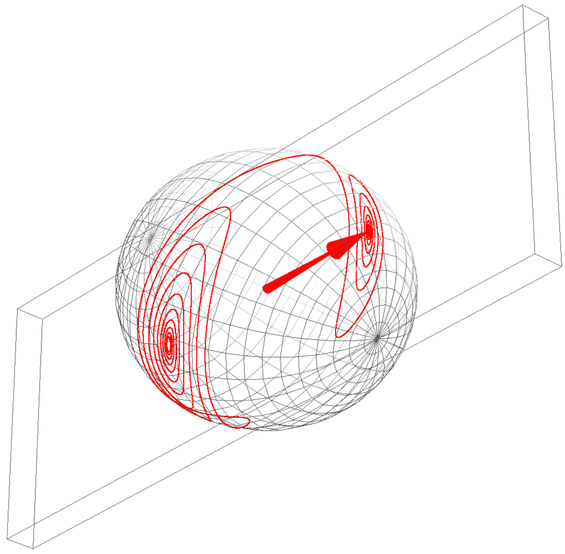
At the same time, the aligned penta-layer configuration, when the magnetizations of the two fixed layers are parallel to each other, was found to have a fairly low spin torque efficiency and, as a consequence, it demands high switching currents (Fuchs et al. 2005). This fact cannot be understood within the formalism employed in (Mojumdar et al. 2010). Indeed, the quantum effects leading to the double resonant conditions and high spin torque efficiency in the anti-parallel structure could be equally well applied to the parallel one. In order to clarify the issue, we performed extensive micromagnetic modeling of the penta-layer structure. In contrast to (Mojumdar et al. 2010) we employ the Slonczewski model (Slonczewski 1996; Slonczewski 2005) for the spin torque. The use of this model is justified in the structures with a free ferromagnetic layer thickness of a few nanometers. Indeed, the electron spins become aligned with the fixed magnetization at a distance approximately 1nm away from the interface (Datta et al. 2009). We investigated the structure CoFe/Cu/Py/AlO_x/CoFe, where Py is $Ni_{81}Fe_{19}$.

MODEL DESCRIPTION

Our simulations are based on the magnetization dynamics described by the Landau-Lifschitz-Gilbert-Slonczewski equation:



(a)



(b)

Figure 2: Visualization of the switching process in the penta-layer structure: (a) from anti-parallel to parallel configuration; (b) from parallel to anti-parallel configuration.

$$\frac{dm}{dt} = -\frac{\gamma}{1+\alpha^2}\cdot((m\times h_{eff}) + \alpha\cdot[m\times(m\times h_{eff})]+ \\ + \frac{g\mu_B j}{e\gamma M_s d}\cdot(g_1(\Theta_1)\cdot(\alpha\cdot(m\times p_1) - [m\times(m\times p_1)])- \\ - g_2(\Theta_2)\cdot(\alpha\cdot(m\times p_2) - [m\times(m\times p_2)]))). \quad (1)$$

Here, γ is the gyromagnetic ratio, α is the Gilbert damping parameter, g is the gyromagnetic splitting factor, μ_B is Bohrs magneton, j is the current density, e is the electron charge, d is the thickness of the free layer, $m = M/M_s$ is the position dependent normalized vector of the magnetization in the free layer, $p_1 = M_{p1}/M_{sp1}$

and $p_2 = M_{p2}/M_{sp2}$ are the normalized magnetizations in the first and second pinned layers, respectively. M_s, M_{sp1}, and M_{sp2} are the saturation magnetizations of the free layer, the first pinned layer, and the second pinned layer, correspondingly. We use Slonczewski's expressions for the gyromagnetic splitting factor in the MTJ with a dielectric layer (Slonczewski 2005)

$$g_1(\Theta) = 0.5 \cdot \eta[1 + \eta^2 \cdot cos(\Theta)]^{-1} \quad (2)$$

and with a metal layer (Slonczewski 1996)

$$g_2(\Theta) = [-4 + (1+\eta)^3(3 + cos(\Theta))/4\eta^{3/2}]^{-1} \quad (3)$$

between the ferromagnetic contacts, respectively. In the penta-layer structure the two spin torques are acting independently on the two opposite interfaces of the free ferromagnetic layer, provided its thickness is larger than the scale on which the electron spins entering into the ferromagnet become aligned to the ferromagnets magnetization. The local effective field is calculated as:

$$h_{eff} = h_{ext} + h_{ani} + h_{exch} + h_{demag} + h_{th} + h_{amp} + h_{ms}. \quad (4)$$

Here, h_{ext} is external field, h_{ani} is anisotropic field, h_{exch} is a exchange field, h_{demag} is a demagnetizing field, h_{th} is a thermal field, h_{amp} is the Ampere field, and h_{ms} is the magnetostatic coupling between the pinned layers and the free layer.
In the uniaxial anisotropy case the anisotropic field is (Miltat and Donahue 2007):

$$h_{ani} = \frac{2K_1}{\mu_0 M_s}(m \cdot u)u, \quad (5)$$

while for the cubic anisotropy it is calculated as:

$$h_{ani} = -\frac{2D}{\mu_0 M_s}m. \quad (6)$$

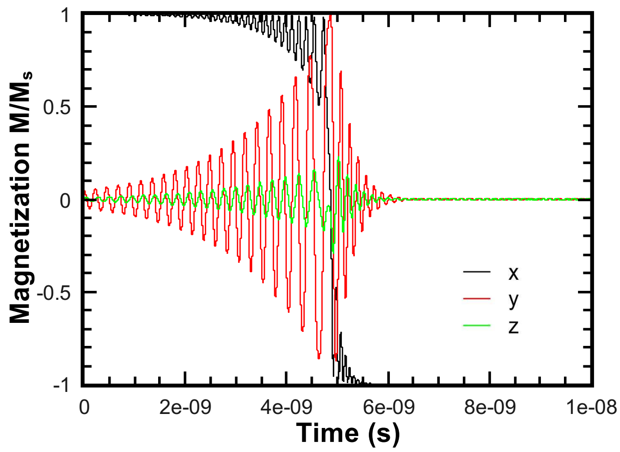
Here, D is the diagonal matrix with entries

$$D_{11} = K_1(m_y^2 + m_z^2) + K_2 m_y^2 m_z^2, \quad (7)$$
$$D_{22} = K_1(m_x^2 + m_z^2) + K_2 m_x^2 m_z^2, \quad (8)$$
$$D_{33} = K_1(m_x^2 + m_y^2) + K_2 m_x^2 m_y^2, \quad (9)$$

K_1 and K_2 are the material-dependent anisotropy coefficients, u is the easy axis, μ_0 is the magnetic constant. The exchange field is calculated as (Miltat and Donahue 2007):

$$h_{exch} = \frac{2A}{\mu_0 M_s}\sum_j((m_j - m)/|r_j|^2). \quad (10)$$

Here, A is the exchange constant.
For calculating the demagnetization field we used the method proposed in (Kákay 2005).



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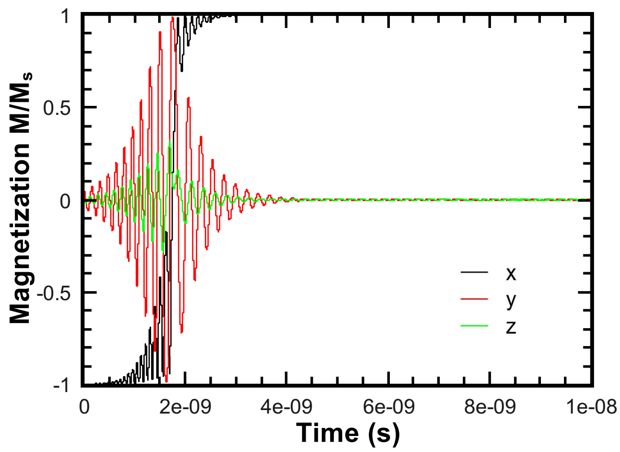


(b)

Figure 3: Evolution of the magnetization of the free ferromagnetic layer during switching in a penta-layer structure: (a) from anti-parallel to parallel configuration; (b) from parallel to anti-parallel configuration.

The thermal field is calculated as (Ito et al. 2006):

$$h_{th} = \sigma \cdot \sqrt{\frac{\alpha}{1+\alpha^2} \cdot \frac{2k_B T}{\gamma \Delta V \Delta t M_s}}. \quad (11)$$

Here, σ is a Gaussian random uncorrelated function, k_B is the Boltzmann constant, ΔV is the volume of cell, Δt is the time step.
The eddy currents field is (Torres et al. 2003):

$$h_{amp,i} = \sum_{j=1..N}\frac{J_j}{4\pi} \times \int_j \frac{r_i - r_j}{r^3}dv. \quad (12)$$

Here, J_j is the current induced on every cell ($j : 1..N$).
For evaluation of the integrals we used methods proposed by (Tomáš 1999).

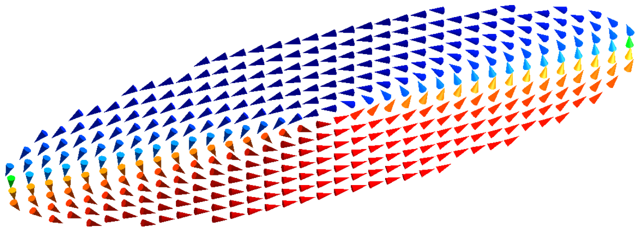
RESULTS

All simulations are performed for the nanopillar structure proposed in (Fuchs et al. 2005). The geometry of the nanopillar is defined as CoFe(8nm)/ AlO_x(0.7nm)/ Py(4nm)/ Cu(6nm)/ CoFe(5nm), with an elliptical crossection (major axes are 90nm and 35nm, correspondingly). The other parameters of our simulations are: T=77K, $\gamma = 2.3245 \cdot 10^5$m/(A·s), α=0.01, $A = 1.3 \cdot 10^{-11}$J/m, $M_s = 644 \cdot 10^3$A/m, $M_{sp} = 1.15 \cdot 10^6$A/m, and η_1=0.3 and η_2=0.35 for the MTJ with the dielectric spacer and the metal spacer, respectively. We simulated the switching process under an applied spin current with the density fixed at $j = 0.1 \cdot 10^8$A/cm^2 and an external magnetic field h_{ext}=26mT applied along the negative direction of the x axis. Simulation results for macro-spin approximation are showed in Fig.2 and Fig.3. The direction of the free layer magnetization is indicated with respect to the magnetization of the pinned layer in the CoFe(8nm)/ AlO_x(0.7nm)/ Py(4nm) MTJ. Fig.3a demonstrates good agreement of the evolution of the magnetization in the free magnetic layer during switching with the results for an ideal elliptical crossection at 77K reported in (Finocchio et al. 2007) and obtained by using micromagnetic modeling.

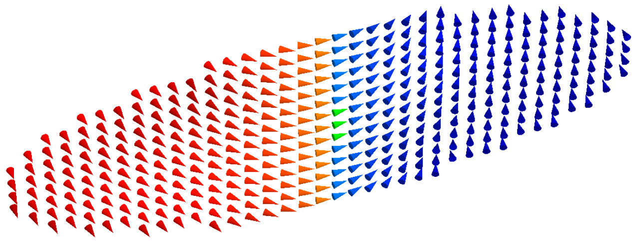
The limitation of the macro-spin approximation is that it cannot take into account the exchange field and the field of the eddy currents. It also does not allow to calculate accurately the magnetostatic coupling between the pinned layers and the free layer, and the demagnetization field. Without these fields it is difficult if not impossible to obtain reliable results.

A snapshots of the the eddy currents field is illustrated in Fig.4a. Fig.4b demonstrates the field of the magnetostatic coupling between the pinned layers and the free layer.

In the following we investigate the switching process from the anti-parallel to the parallel state with full micromagnetic simulation and for two types of initial conditions for the magnetization (Fig.5). In the case of unidirectional initial magnetization parallel to the x axis we obtain practically the same result as for our macro-spin model. However, in the case, when the magnetization was allowed first to relax, the switching time is two times longer than in the case of unidirectional initial magnetization. This result demonstrates the importance of properly accounting for the magnetization relaxation under the influence of the external fields to correctly obtain the initial magnetization.



(a)



(b)

Figure 4: Snapshots of: (a) the eddy currents field; (b) the magnetostatic coupling between the pinned layers and the free layer.

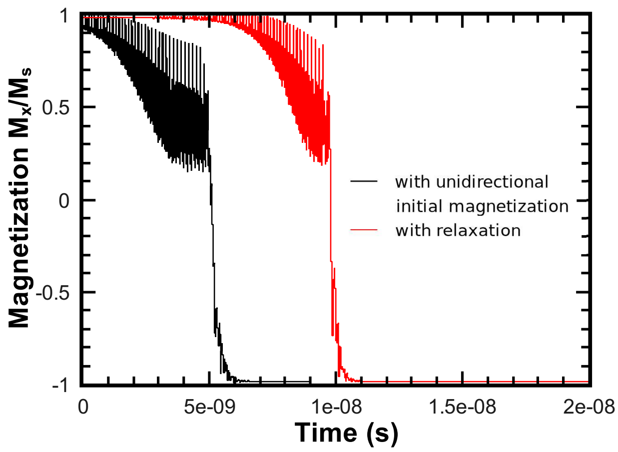


Figure 5: Switching process from anti-parallel to parallel configuration in a penta-layer structure for two different initial magnetization: the unidirectional magnetization along the x and the magnetization after the relaxation process.

CONCLUSION

Magnetic tunnel junctions with the magnetization of the two side layers fixed are studied by means of a macro-spin approximation and the extensive micromagnetic calculations. Our results demonstrate that, despite all the limitations of a macro-spin model, it can provide fast and relatively accurate results for a certain set of parameters. We also show the importance of properly accounting for the magnetization relaxation under the influence of the external fields. Our simulation environment is thus perfectly suited for optimization of STTRAM cells.

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