Study of Self-Accelerating Switching in MTJs with Composite Free Layer by Micromagnetic Simulations

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Abstract—**We analyze the peculiarities of the magnetic dynamics of MTJs with a composite free layer. The composite magnetic layer consists of two half-ellipses separated by a non-magnetic spacer. We show that the switching barrier in these MTJs becomes practically equal to the thermal stability barrier. We investigate the dependence of the switching time and thermal stability on the geometry of these MTJs. The physical reasons for the distribution of the switching times narrowing in penta-layer MTJs with a composite free layer are revealed.**

Keywords-MTJ; micromagnetic modeling; STT-MRAM; composite free layer

I. Introduction

Magnetoresistive random access memory with spin transfer torque (STT-MRAM) is a promising candidate for future universal memory [1], [2], [3]. The basic element of an STT-MRAM cell is a magnetic tunnel junction (MTJ), a sandwich of two magnetic layers separated by a thin non-magnetic spacer. While the magnetization of the pinned layer is fixed due to 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. The switching in STT-MRAM occurs due to the spin-polarized current flowing through the MTJ.

Perpendicular MTJs (p-MTJs) with an interface-induced anisotropy [4] show potential, but still require damping reduction and thermal stability increase [5]. Therefore, the research of finding new materials and architectures for MTJ structures is intensifying.

A penta-layer MTJ with a composite free layer was recently proposed in [6]. The free magnetic layer of such a structure consists of two half-ellipses separated by a non-magnetic spacer (Fig.1, right). MTJs with a composite free layer have demonstrated a substantial decrease of the switching time (Fig.2) and of the required switching current [7].

In contrast to [4], the magnetization of the magnetic layers in the proposed MTJ lies in-plane. This allows to broaden substantially the scope of the magnetic materials suited for constructing MTJs and to boost the thermal stability factor while keeping the switching fast.

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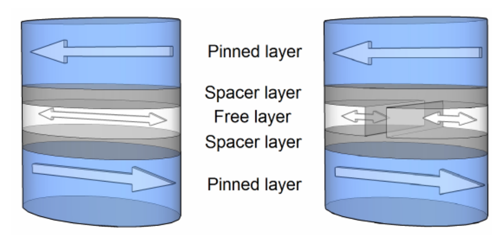

Figure 1. Schematic illustration of penta-layer MTJs with monolithic (left) and composite free layer (right).

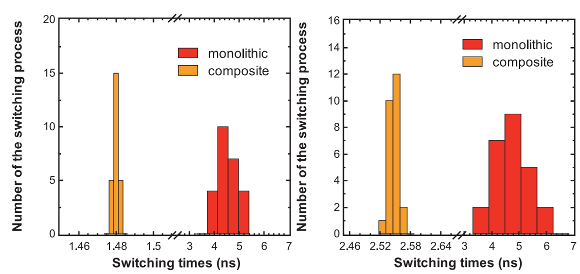

Figure 2. Distributions of the switching times for an MTJ of $75\times25\text{nm}^2$ (left) and $155\times60\text{nm}^2$ (right) cross-section with monolithic and composite free layer.

In early work [6], [7] a decrease of switching time and/or switching current was associated only with an effectively non-zero angle between the fixed magnetization and the magnetization in the composite free layer: this results in an enhanced spin transfer torque, when the current starts flowing.

Here we reveal additional physical reasons for the switching time reduction and narrowing of the distribution of the switching time, discuss scalability, and dependence of the switching time and thermal stability on the geometry of these MTJs.

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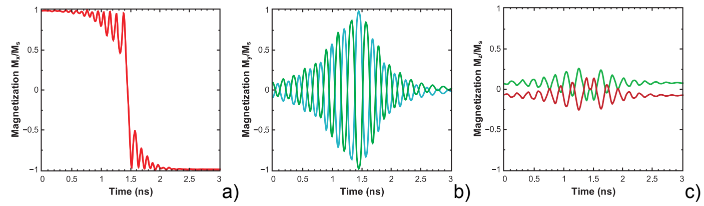

Figure 3. Magnetization components as a function of time for an MTJ element of 75×25nm^2 with a composite free layer. The magnetization of the left and right half is shown separately.

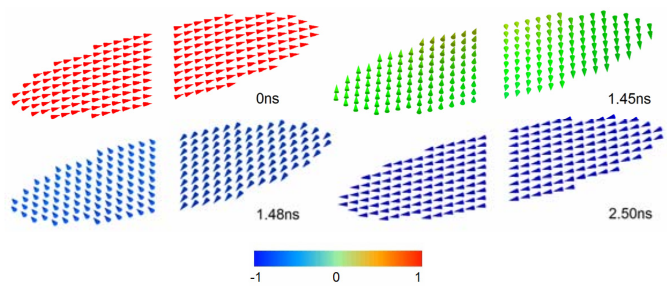

Figure 4. Snapshots of the switching process for an MTJ with a composite free layer with dimensions 75×25nm^2. The direction of the magnetization is shown by unit vectors, color indicates the value of the *x*-component of magnetization, the *x*-axis is directed along the long axis of the ellipse.

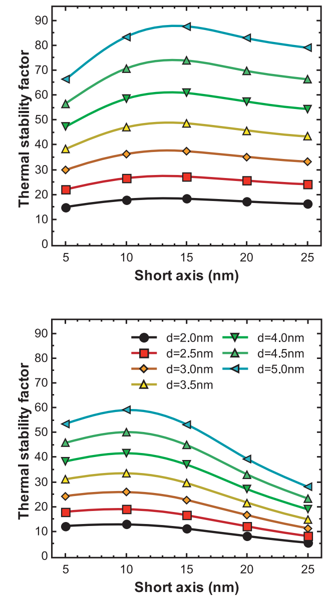

Figure 5. Thermal stability factor for MTJs with monolithic (top) and composite (bottom) free layer as function of the short axis. The long axis is fixed at 52.5nm and the thickness of the fixed layers are 5nm.

II. Model Description

The simulations of a penta-layer MTJ are based on the magnetization dynamics described by the Landau-Lifschitz-Gilbert (LLG) equation with additional spin torque terms [6]:

$$\frac{dm}{dt} = -\frac{\gamma}{1+\alpha^2}\cdot\Big(\big(m\times h_{eff}\big)+\alpha\cdot\big[m\times\big(m\times h_{eff}\big)\big] + \frac{g\mu_B j}{e\gamma M_s d}\cdot\big(g(\theta_1)\cdot\big(\alpha\cdot(m\times p_1)-\big[m\times(m\times p_1)\big]\big) - g(\theta_2)\cdot\big(\alpha\cdot(m\times p_2)-\big[m\times(m\times p_2)\big]\big)\big)\Big). \quad (1)$$

Here, γ=2.3245·10^{5}m/(A·s) is the gyromagnetic ratio, α is the Gilbert damping parameter, μ_B is Bohr's 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 MTJ with a dielectric layer [8]:

$$g(\theta) = 0.5\cdot\eta\cdot\left[1+\eta^2\cdot\cos(\theta)\right]^{-1}. \quad (2)$$

The local effective field is calculated as:

$$h_{eff} = h_{ext} + h_{ani} + h_{exch} + h_{demag} + h_{th} + h_{amp} + h_{ms}. \quad (3)$$

Here, h_{ext} is the external field, h_{ani} is the magnetic anisotropy field, h_{exch} is the exchange field, h_{demag} is the demagnetizing field, h_{th} is the thermal field, h_{amp} is the Ampere field, and h_{ms} is the magnetostatic coupling between the pinned layers and the free layer.

III. Result And Discussion

The simulations are performed for a nanopillar CoFeB/ MgO(1nm)/ CoFeB/ MgO(1nm)/ CoFeB MTJ, for a broad range of elliptical cross sections and different thicknesses of pinned layers and free layer. The other model parameters are: T=300K, $M_s=M_{sp}$=8.9·10^{5}A/m, A=1·10^{-11}J/m, K=2·10^3 J/m^3, α=0.005, and η=0.63 [9].

For demonstration of the reasons of fast switching we look at the magnetization dynamics of the left and right part of the composite free layer separately (Fig.3). First we consider a structure with an elliptical cross-section 75×25nm^2 (CoFeB(5nm)/ MgO(1nm)/ CoFeB(2nm)/ MgO(1nm)/ CoFeB(5nm)). In the middle layer the central 5nm stripe is removed. Fig.3b and Fig.3c show that the switching processes of the left and right part of the composite free layer occur in opposite senses to each other. Magnetization snapshots shown in Fig.4 confirm the opposite phase character of switching. It is important that the switching mostly occurs in the *x*-*y* plane (Fig.3b, Fig.3c, and Fig.4,). This means that, as in p-MTJs, the switching barrier in an MTJ with a composite free layer becomes practically equal to the thermal stability barrier defined by the shape anisotropy.

Next we compare the thermal stability factor [10] for MTJs with composite and monolithic free layers. Due to the removal of the central region, the shape anisotropy and the thermal barrier of the structure with a composite layer is slightly decreased. To increase the thermal stability factor it is sufficient to increase the thickness of the free layer and/or the aspect ratio. Fig.5 shows the thermal stability factors for MTJs with monolithic (top) and composite (bottom) free layers as a function of the short axis. An MTJ with $52.5\times10nm^2$ cross section and 5nm thickness of the free layer has a thermal stability factor ~60kT, which exceeds that for the p-MTJ demonstrated so far [11].

Equality of the switching barrier and the thermal barrier in composite structures results in an almost linear increase of the switching time in these MTJs with increasing thickness of the free layer and/or aspect ratio (Fig.6a). A similar dependence is shown in Fig.6b for a monolithic structure. The influence of the MTJ geometry on the switching acceleration in a MTJs with a composite free layer relative to the one with a monolithic layer is shown in Fig.7. The long axis is fixed at 52.5nm. Each point is a result of statistical averaging over 30 different realizations of the switching process. An almost 3-fold reduction of the switching time is achieved in MTJs with a composite free layer without sacrificing much on thermal stability.

We now compare the standard deviations of the switching time distributions in the monolithic and composite structure shown in Fig.8. We find the width of the switching time distribution for MTJs with a composite free layer can be almost ~2000 times narrower than that for MTJs with a monolithic free layer. The dependence of the value of the standard deviation on composite layer thickness and aspect ratio is also shown in Fig.9. An MTJ with $52.5\times25nm^2$ cross section has a standard deviation of the switching time ~10^{-3}ns, while an MTJ with $52.5\times10nm^2$ cross section has the standard deviation of the switching time 0.3-1.6ns.

In order to find a physical explanation for the distribution narrowing, we analyze the switching process in detail. A schematic illustration of the self-stabilization and self-acceleration principle of switching in a composite free layer is explained in Fig.10. Each half of the free layer generates a stray magnetic field which influences the other half and helps stabilizing the switching process. This stray magnetic field increases with increasing of the short axis which leads to the switching times distribution narrowing. Before the moment when the magnetizations of different halves of the composite layer are in opposite directions to each other (Fig.10b) this stray magnetic field acts as a stabilizing factor of switching (Fig.10a). After the opposite magnetization state the stray magnetic fields accelerate switching as illustrated in Fig.10c.

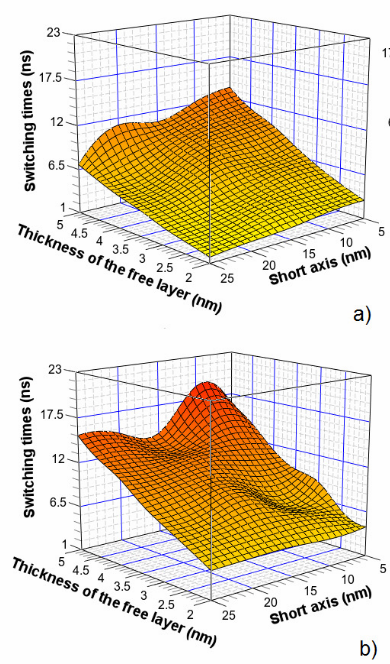

Figure 6. Switching times in the composite structure (a) and monolithic structure (b) as function of thickness of the free layer and short axis length. The long axis is fixed at 52.5nm and the thickness of the fixed layers are 5nm.

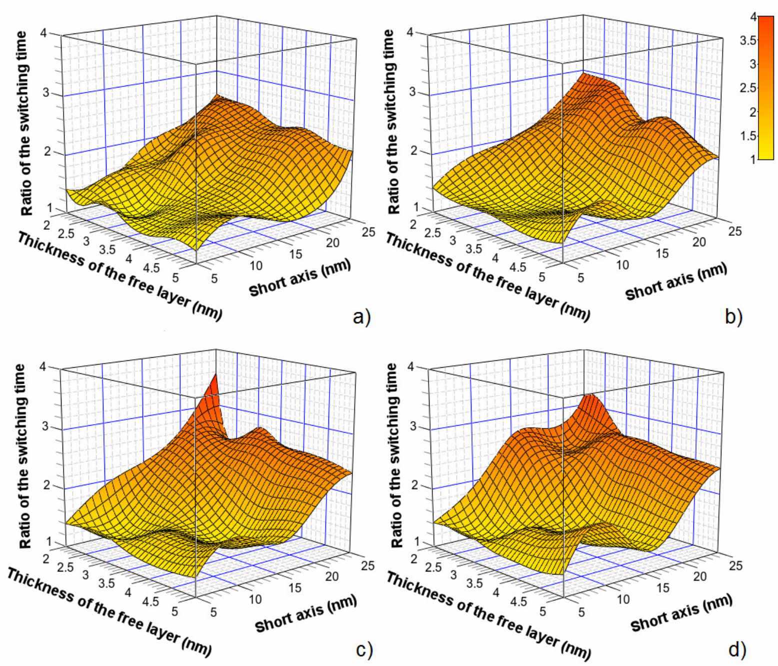

Figure 7. Ratio of the switching times in the monolithic structure and composite structure as function of thickness of the free layer and short axis length. The long axis is fixed at 52.5nm. Dependences are shown for the thickness of the fixed layers: 5nm (a), 10nm (b), 15nm (c), 20nm (d).

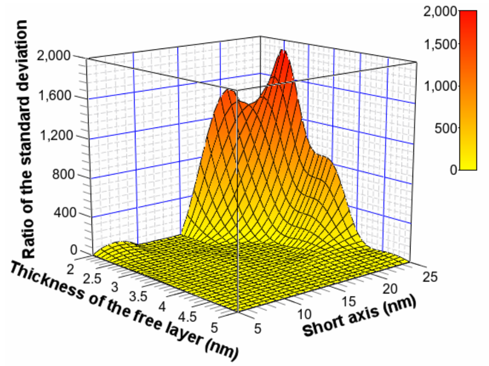

Figure 8. Ratio of the standard deviation of the switching time in the monolithic structure and composite structure as function of thickness of the free layer and short axis length. The long axis is fixed at 52.5nm and the thickness of the fixed layers are 10nm.

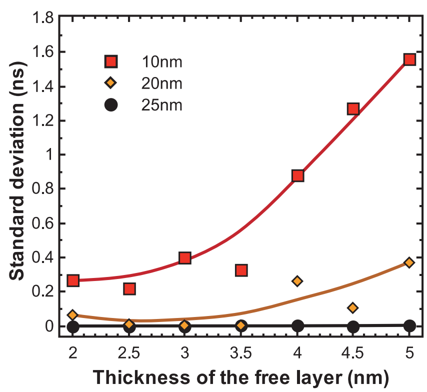

Figure 9. The standard deviation of the switching time distribution in the composite structure as a function of thickness of the free layer. The long axis is fixed at 52.5nm and the thickness of the fixed layers are 15nm. Dependences are shown for the short axis of 10nm, 20nm, and 25nm.

IV. Conclusion

We demonstrated that an almost 3-fold decrease of the switching time is achieved in MTJs with a composite layer. As in p-MTJs, in such structures the switching energy is practically equal to the thermal stability barrier. Due to the removal of the central region in the monolithic structure the shape anisotropy is slightly decreased together with the thermal stability factor. To boost the thermal stability factor in composite structures it is sufficient to increase the thickness of the free layer and/or the aspect ratio, so the thermal stability factor exceeds that for p-MTJs demonstrated so far. Also a very narrow distribution of switching times is found for the composite structure. Therefore, the investigated MTJ offers great potential for performance optimization of STT-MRAM devices.

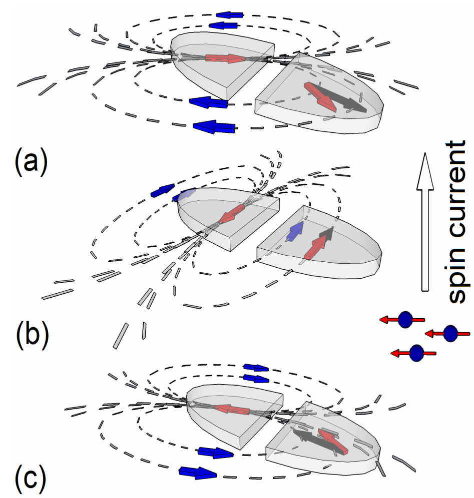

Figure 10. Schematic illustration of the state with self-stabilization direction of the stray magnetic field (a), opposite magnetization state (b), and self-acceleration switching state (c) in an MTJ with a composite free layer.

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