MTJs with a Composite Free Layer for High-Speed Spin Transfer Torque RAM: Micromagnetic Simulations

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***Abstract*—We demonstrate a substantial decrease of the switching time in penta-layer MTJs with a composite free layer regardless of the size and aspect ratio of the MTJ. The composite magnetic layer consists of two half-ellipses separated by a non-magnetic spacer. We analyze the peculiarities of the magnetic dynamics of these MTJs and reveal the physical reason for the decrease of the switching time. The scaling potential based on an analysis of the thermal stability is discussed. Furthermore, we outline the method for increasing the thermal.**

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

I. INTRODUCTION

Memories based on charge storage are gradually approaching the physical limits of scalability and conceptually new types of memories based on a different storage principle are gaining momentum [1]. Magnetoresistive random access memory with spin-transfer torque (STT-MRAM) is a promising candidate for future universal memory [2], [3]. The basic element of an STT-MRAM is a magnetic tunnel junction (MTJ), a sandwich of two magnetic layers separated by a thin nonmagnetic 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. Switching in STT-MRAM occurs due to the spin-polarized current flowing through the MTJ.

Different architectures of MTJ are available: three-layer with in-plane magnetization of the free layer (in-plane MTJs) [4], [5], [6], in-plane penta-layer MTJs [7], three-layer MTJs with perpendicular magnetization (p-MTJs) [8], and others.

Perpendicular MTJs with interface-induced anisotropy demonstrate a reduction of the switching energy, but still require damping reduction and thermal stability increase [9]. Therefore, research about new materials and architectures for MTJ structures is intensifying.

A penta-layer MTJ with a composite free layer (Fig.1) proposed in [10] has demonstrated a substantial decrease of the switching time and current reduction [11] as compared to an MTJ with a monolithic free layer. The composite magnetic layer consists of two half-ellipses separated by a non-magnetic spacer (Fig.2b). In contrast to p-MTJs [8], the magnetization of the magnetic layers lies in-plane. This allows to broaden substantially the scope of the magnetic materials suited for constructing MTJs.

In early work [10], [11] a decrease of switching time and/or switching current density is associated only with an effectively non-zero angle between the fixed magnetization and the magnetization in the composite free layer. This results in enhanced spin transfer torque, when the current starts flowing.

Here we reveal additional physical reasons for the switching time reduction, discuss scalability, and outline a method for increasing the thermal stability of MTJs with a composite free layer.

II. MODEL DESCRIPTION

The simulations are based on the magnetization dynamics described by the Landau-Lifschitz-Gilbert (LLG) equation with additional spin torque terms [10]:

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

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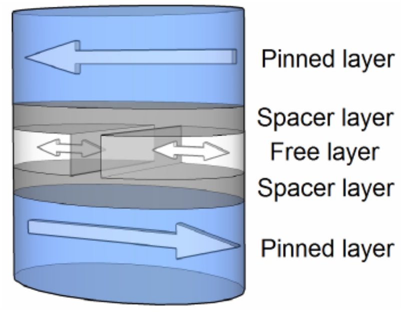

Figure 1. Schematic illustration of a penta-layer MTJ with composite free layer.

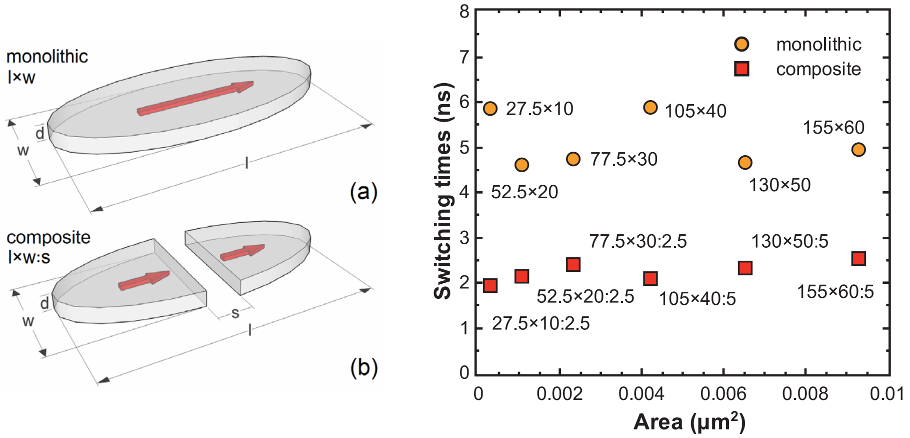

Figure 2. Average value of the switching times for MTJs with monolithic (length×width) and composite (length×width:separation) free layer as function of the cross section area.

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 [12]:

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

The local effective field is calculated as:

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

In addition to the standard external h_{ext} and the anisotropic h_{ani} micromagnetic contributions we also include the exchange field h_{exch} and the demagnetizing field h_{demag}. h_{th} is the thermal field [13], h_{amp} is the Ampere field [14], and h_{ms} is the magnetostatic coupling between the pinned layers and the free layer.

III. RESULTS AND DISCUSSION

All simulations are performed for a nanopillar CoFeB(5nm)/ MgO(1nm)/ CoFeB/ MgO(1nm)/ CoFeB(5nm) MTJ, for a broad range of elliptical cross sections from 27.5×10nm^2 to 155×60nm^2. 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 [15].

First we investigate the dependence of the switching time on the aspect ratio of the free layer. The aspect ratio is chosen so that for a composite free layer ((*length-separation*)/*2*)/*width*=1.25. Fig.2 shows a decrease of the switching time in MTJs with a composite free layer as compared to that of MTJs with a monolithic free layer of similar dimensions, for all cross section areas. Each point is a result of statistical averaging with respect to 50 different realizations of the switching process. Our results clearly show a linear dependence of the switching time in the composite structures on the ratio *length*/*separation*.

In order to find a physical explanation for the switching time reduction in composite structures, we analyze the switching process in a monolithic structure with a gradual decrease of the exchange coefficient between the central elements (Fig.3). The switching time decreases with decreasing exchange and becomes practically equal to the switching time in a structure with a composite free layer, when exchange between the central elements→0.

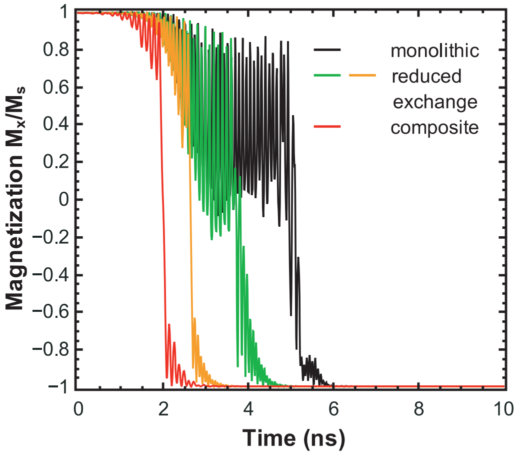

Figure 3. The switching process for an MTJ with the cross section 90×35nm^2 for different exchange between the central elements.

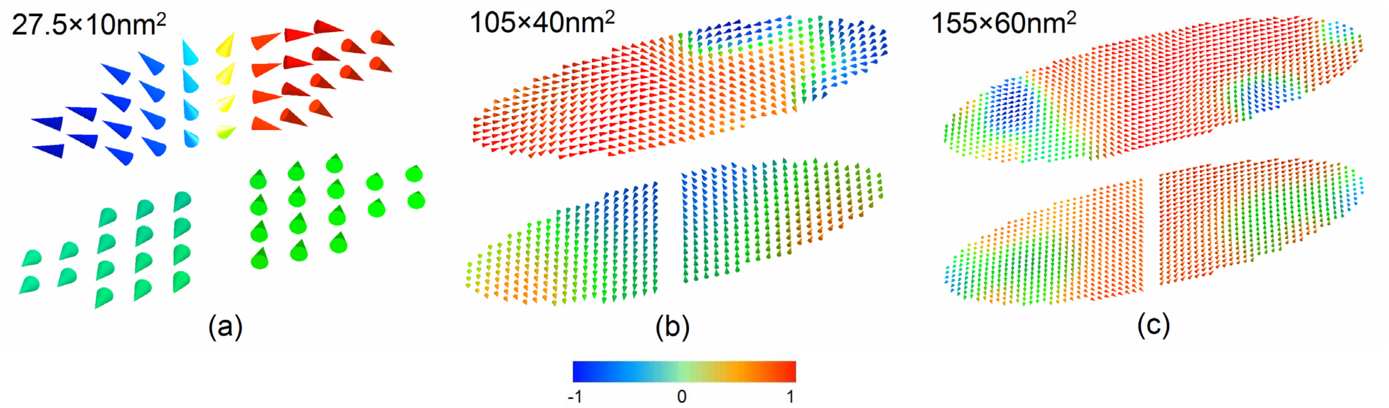

Figure 4. Snapshots of the switching process for a MTJ with (top) monolithic and (bottom) composite free layer. The direction of the magnetization is shown as the unit vectors, color indicates the *x*-component of the magnetization, the *x*-axis is directed along the long axis of the ellipse.

When the central region is removed, the end domains become virtually independent and switch without forming domain walls (Fig.4). Magnetizations of each half of the composite layer are in opposite directions and the switching mostly occurs in the *x-y* plane (Fig.5). This type of switching requires less energy and therefore leads to the switching acceleration under the influence of a similar spin current.

Next we compare the thermal stability factor [16] for MTJs with composite and monolithic free layers. Due to the removal of the central region in the monolithic structure the shape anisotropy is decreased together with the thermal stability factor (Fig.6). To increase the thermal stability factor it is sufficient to increase the thickness of the free layer and/or the aspect ratio. Fig.7 shows simulation results for MTJs with elliptical cross sections from 52.5×10nm^2 to 52.5×20nm^2. Calculations are made for mesh cells sizes from 0.5×0.5nm^2 to 2.5×2.5nm^2. Our simulation show almost identical results for all mesh cells sizes, therefore, for further modeling of these devices, we use 2.5×2.5nm^2 mesh size.

Our results indicate that MTJs with a composite layer with 52.5×10nm^2 cross section and 5nm thickness of the free layer have a good retention with a thermal stability factor ~60kT, which exceeds that for the p-MTJ demonstrated so far [17].

The influence of the MTJ geometry on switching is shown in Fig.8. The long axis is fixed at 52.5nm. Each point is a result of statistical averaging with respect to 25 different realizations of the switching process. An almost threefold decrease of the switching time is achieved in MTJs with a composite layer without sacrificing on thermal stability.

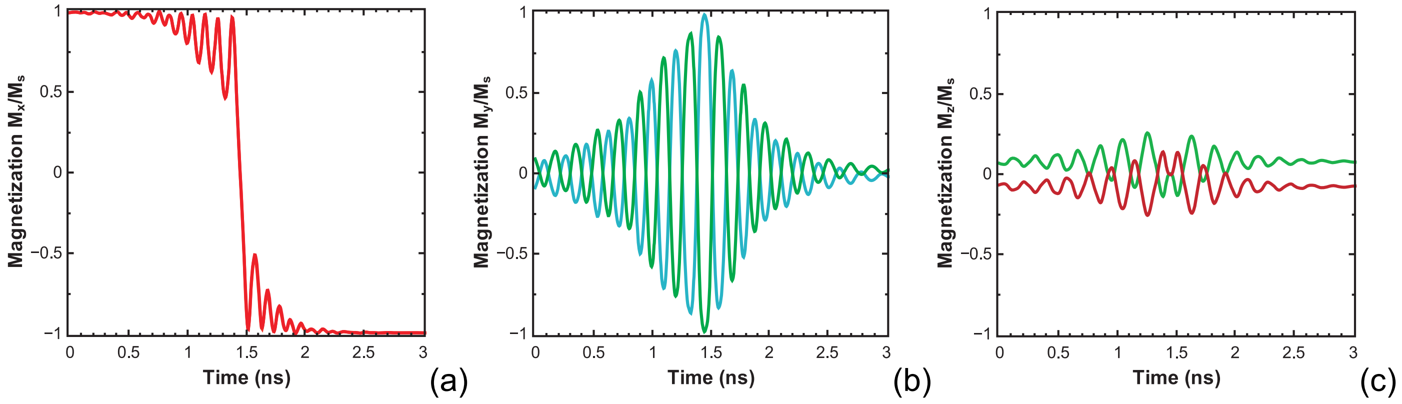

Figure 5. Simulated volume-averaged magnetization components as a function of time for an MTJ element of 75×25nm^2 and composite free layer. The magnetization of the left and right half is shown separately.

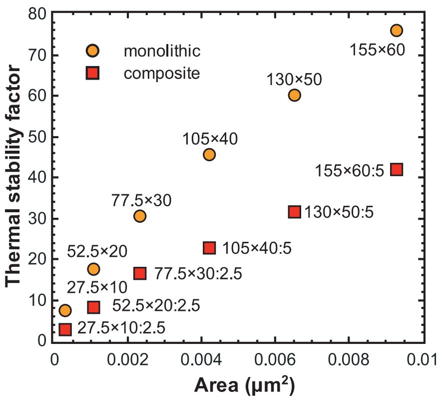

Figure 6. Thermal stability factor for MTJs with monolithic (l×w) and composite (l×w:s) free layer as function of the cross section area

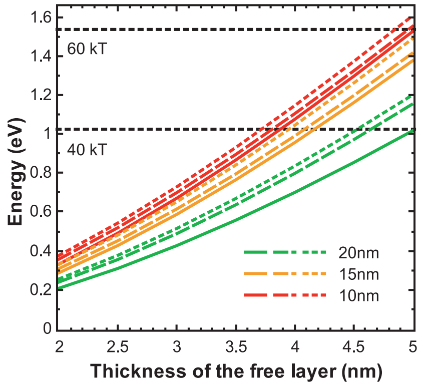

Figure 7. Thermal stability factor for MTJs with a composite free layer as function of the thickness of the free layer. The long axis is fixed at 52.5nm. Dependences are shown for simulations with mesh cells: 2.5×2.5nm^2 (solid lines), 1.25×1.25nm^2 (dashed lines), and 0.5×0.5nm^2 (dotted lines).

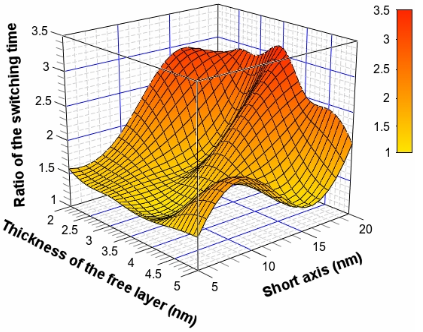

Figure 8. Ratio of the switching times in the monolithic structure and composite structure as function of thickness of the free layer and short axis length. The long axis is fixed at 52.5nm.

IV. CONCLUSION

Magnetic tunnel junctions with a composite free layer are studied by means of extensive micromagnetic calculations. Our simulations show a decrease of the switching time in MTJs with a composite free layer as compared to that with a monolithic free layer of similar dimensions for all cross section areas. As physical explanation we found that, when the central region is removed, the end domains become virtually independent and switch without forming domain walls. This type of switching requires less energy and therefore leads to the switching acceleration. 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 it is sufficient to increase the thickness of the free layer and/or the aspect ratio. Therefore, the investigated structure offers great potential for performance optimization of STT-MRAM devices.

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