Phys. Status Solidi RRL **5**, No. 12, 420–422 (2011) / **DOI** 10.1002/pssr.201105376

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Reduction of switching time in pentalayer magnetic tunnel junctions with a composite-free layer

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Received 30 July 2011, revised 3 September 2011, accepted 5 September 2011

Keywords spin transfer torque, RAM, MRAM, magnetic tunnel junction, micromagnetic modeling

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We have performed micromagnetic simulations of the magnetization dynamics of the composite-free magnetic layer in a pentalayer structure. We have found a substantial decrease of the switching time in this system as compared to the pentalayer structure of similar dimensions with a monolithic free layer. The physical reasons for the switching time reduction at the same current density are discussed.

1 Introduction

Memory cells based on electric charge storage are rapidly approaching their physical limits of scalability. The increasing demand for minimization of microelectronic devices 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 [1].

The theoretical predictions [2] and the experiments [3] of spin transfer switching demonstrated that the spin transfer torque random access memory (STTRAM) is one of the promising candidates for future universal memory. STTRAM is characterized by small cell size ($4F^2$), fast access time (less than 10 ns), high endurance (10^{16}), and long retention time.

The basic element of the STTRAM 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 during the fabrication process, the magnetization direction of the free layer can be switched between the two states parallel and antiparallel 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 [4].

It has been demonstrated [5] that the critical current density is decreased in the pentalayer magnetic tunnel junction shown in Fig. 1a. The structure represents a magnetic tunnel junction composed of 5 layers, with the magnetizations of the two side layers being antiparallel.

In this Letter we briefly describe the results of our micromagnetic simulations of a pentalayer structure with a composite-free layer (Fig. 1b). We report a substantial decrease of the switching time in this system as compared to the pentalayer structure of similar dimensions with the monolithic free layer. The physical reasons for the switching time reduction at the same current density are highlighted.

2 Model

We investigated the structure CoFe/spacer (1 nm)/Py (4 nm)/spacer (1 nm)/CoFe (Py is $Ni_{81}Fe_{19}$) with an elliptical cross-section (major axes 90 nm and 35 nm, respectively). The system with a composite ferromagnetic layer is obtained by removing a central stripe of width 5 nm from the monolithic free layer. The micromagnetic simula-

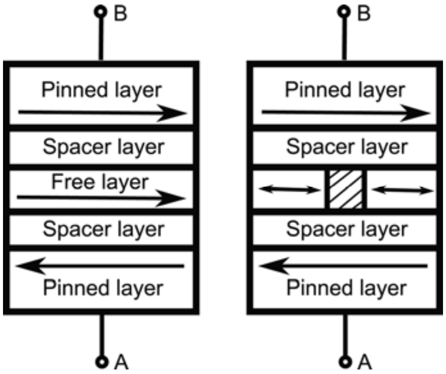

Figure 1 Schematic illustration of the pentalayer MTJ with monolithic (left) and composite-free layer (right).

tions are based on the magnetization dynamics described by the Landau–Lifschitz–Gilbert equation:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\frac{\gamma}{1+\alpha^2}((m\times h_{\mathrm{eff}})+\alpha[m\times(m\times h_{\mathrm{eff}})]) + \frac{g\mu_{\mathrm{B}} j}{e\gamma M_{\mathrm{s}} d}(g_1(\Theta_1)(\alpha(m\times p_1)-[m\times(m\times p_1)]) - g_2(\Theta_2)(\alpha(m\times p_2)-[m\times(m\times p_2)]))\,. \tag{1}$$

γ is the gyromagnetic ratio, α is the Gilbert damping parameter, g is the gyromagnetic splitting factor, μ_{B} is Bohr's magneton, j is the current density, e is the electron charge, d is the thickness of the free Py layer, $m = M/M_{\mathrm{s}}$ is the position dependent normalized vector of the magnetization in the free layer, $p_1 = M_{\mathrm{p1}}/M_{\mathrm{sp1}}$ and $p_2 = M_{\mathrm{p2}}/M_{\mathrm{sp2}}$ 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, respectively. We use Slonczewski's expressions for the MTJ with a dielectric layer [6]

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

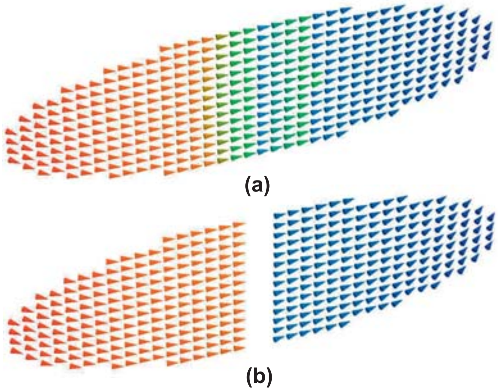

Figure 2 (online colour at: www.pss-rapid.com) Snapshots of the initial magnetization: (a) monolithic free layer, (b) composite-free layer.

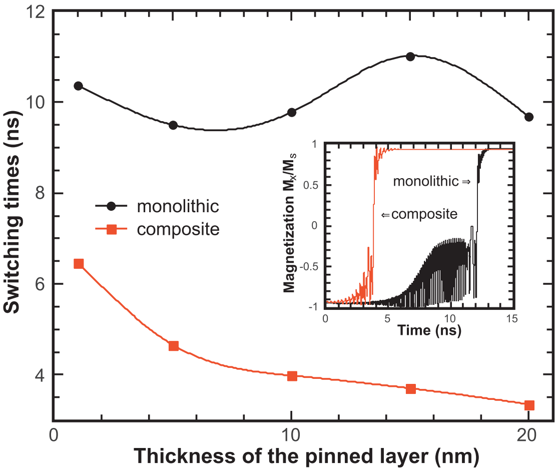

Figure 3 (online colour at: www.pss-rapid.com) Absolute values of the switching times for MTJs with monolithic and composite-free layer as the function of the pinned layer thickness. The inset shows the switching process for an MTJ with composite and monolithic free layer for a pinned layer thickness of 15 nm.

and with a metal layer [2]

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

between the ferromagnetic contacts, respectively. In the pentalayer 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

$$h_{\mathrm{eff}} = h_{\mathrm{ext}} + h_{\mathrm{ani}} + h_{\mathrm{exch}} + h_{\mathrm{demag}} + h_{\mathrm{th}} + h_{\mathrm{amp}} + h_{\mathrm{ms}}\,. \tag{4}$$

h_{ext} is the external field, h_{ani} is the anisotropic field, h_{exch} is an exchange field, h_{demag} is a demagnetizing field, h_{th} is a thermal field, and h_{amp} is the Ampere field. The thermal field is calculated as [7]

$$h_{\mathrm{th}} = \sigma\sqrt{\frac{\alpha}{1+\alpha^2}\,\frac{2k_{\mathrm{B}}T}{\gamma\,\Delta V\Delta t\,M_{\mathrm{s}}}}\,. \tag{5}$$

σ is an uncorrelated Gaussian random variable, k_{B} is the Boltzmann constant, ΔV is the cell volume, Δt is the time step.

Contrary to the standard consideration we do not assume the pinned layers being fully compensated. They produce the magnetostatic field h_{ms}, which additionally couples the pinned layers and the free layer, thus offering an additional degree of freedom to improve the characteristics of the system.

3 Results Figure 2 illustrates the distribution of the magnetization in the free monolithic (a) and composite (b) layer after the relaxation according to Eq. (1) by including the magnetostatic field h_{ms}. This field causes the magneti-

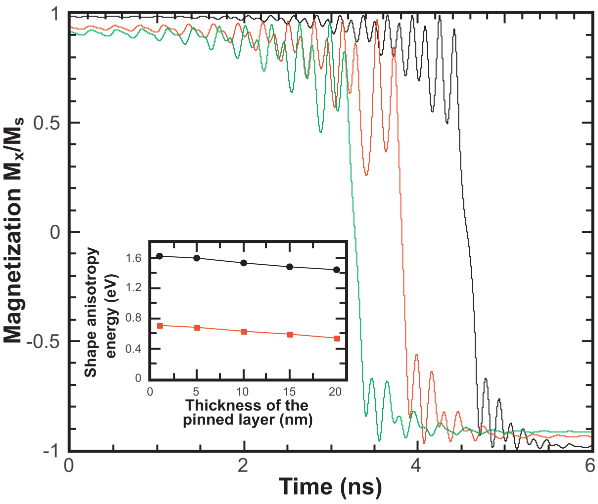

Figure 4 (online colour at: www.pss-rapid.com) Switching process for MTJs with composite-free layer for the pinned layer thicknesses of 5 nm, 15 nm, and 20 nm (from right to left). The inset shows the shape anisotropy energy as the function of the thickness of the pinned layer for monolithic (filled circles) and composite (filled squares) free layer.

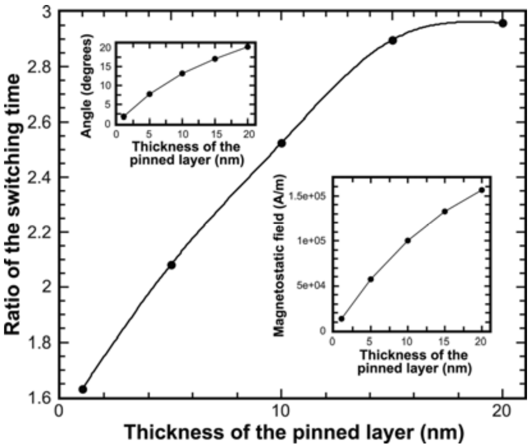

Figure 5 Ratio of the switching time in the monolithic structure vs. in the composite structure as function of the thickness of the pinned layer. The insets show the averaged initial angle (top) and the dependence of the absolute values of the z-component of the averaged magnetostatic field (bottom).

zation to tilt out of the $x-y$ plane. The non-zero angle between the fixed magnetization and the magnetization in the free layer results in the enhanced spin transfer torque, when the current starts flowing. In the case of the monolithic structure, however, the torque remains marginal in the central region, where the magnetization is along the x-axis. As the amplitude of the end domains precession increases, the central region experiences almost no spin torque and preserves its initial orientation along the x-axis, thus preventing the whole layer from alternating its magnetization orientation. This is, however, not the case when the central region is removed in the composite structure and the end domains become virtually independent. Figure 3 demonstrates a substantial decrease of the switching time in the pentalayer structure with the composite-free layer, for the same current density, as a function of the thickness of the pinned ferromagnetic layers. The switching process for the pinned layer thicknesses of 5 nm, 15 nm, and 20 nm is shown in Fig. 4. Due to the removal of the central region which represented the “bottleneck” for switching in the monolithic structure the shape anisotropy energy is decreased (Fig. 4, inset). However, its value is still sufficiently large for guaranteeing the thermal stability at operation conditions [5].

The ratio of the switching times is shown in Fig. 5. The switching time in a pentalayer structure with a composite-free layer is decreasing with thickness of the pinned layers increased. This is due to the fact that the z-component of the magnetostatic field h_{ms} (Fig. 5, bottom inset) is increased together with the pinned layer thickness causing a larger initial angle (Fig. 5, top inset) between the relaxed magnetization in the domains of the free layer and the magnetization of the pinned layer, larger torque and, as a consequence, a shorter switching time.

4 Conclusion We have demonstrated that the switching time in a non-compensated pentalayer structure with anti-parallel orientation of the pinned layers can be further decreased by considering a composite-free ferromagnetic layer without the central region. The switching time is decreased due to the removal of the switching bottleneck due to the central region and by tilting the magnetization of the end domains in the magnetostatic field of the uncompensated pinned layers, creating an angle between the pinned and free magnetization directions and thus enhancing torque.

Acknowledgements This research is supported by the European Research Council through the grant #247056 MOSILSPIN.

References

[1] M. H. Kryder and C. S. Kim, IEEE Trans. Magn. **45**, 3406 (2009).
[2] J. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[3] H. Zhao, A. Lyle, Y. Zhang, P. K. Amiri, G. Rowlands, Z. Zeng, J. Katine, H. Jiang, K. Galatsis, K. L. Wang. I. N. Krivorotov, and J.-P. Wang, J. Appl. Phys. **109**, 07C720 (2011).
[4] R. Sbiaa, S. Y. H. Lua, R. Law, H. Meng, R. Lye, and H. K. Tan, J. Appl. Phys. **109**, 07C707 (2011).
[5] G. D. Fuchs, I. N. Krivorotov, P. M. Braganca, N. C. Emley, A. G. F. Garcia, D. C. Ralph, and R. A. Buhrman, Appl. Phys. Lett. **86**, 152509 (2005).
[6] J. Slonczewski, Phys. Rev. B **71**, 024411 (2005).
[7] K. Ito, T. Devolder, C. Chappert, M. J. Carey, and J. A. Katine, J. Appl. Phys. **99**, 08G519 (2006).