Optimization of the Penta-Layer Magnetic Tunnel Junction for Fast STTRAM Switching

Alexander Makarov, Viktor Sverdlov, Dmitri Osintsev, and Siegfried Selberherr

Institute for Microelectronics, TU Wien, Gußhausstraße 27-29, 1040 Vienna, Austria
{makarov|sverdlov|osintsev|selberherr}@iue.tuwien.ac.at

Memory cells based on electric charge storage, such as flash memory, are rapidly approaching the physical limits of scalability. The spin transfer torque random access memory (STTRAM) is one of the promising candidates for future universal memory [1]. 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 (Fig. 1a). 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 between the two states occurs due to spin-polarized current flowing through the MTJ. The reduction of the current density required for switching and the increase of the switching speed are the most important challenges in this area [2]. Several strategies have been proposed to decrease the switching time below a few nanoseconds: by pre-charging with a bias current [3], by combining a spin-polarized current together with a small radio frequency field [4], and by exploiting magnetic perpendicular anisotropy [5]. Measurements performed in [6] showed a decrease in the critical current density for the penta-layer MTJ (Fig. 1b) compared with the tri-layer MTJ.

In this work we investigate the dynamics of the switching process in a MTJ composed of five layers, where the magnetizations of the two layers are fixed, with a composite soft magnetic layer and compared it with the MTJ with a monolithic soft layer. We performed extensive micromagnetic modeling of the penta-layer structures by employing the Slonczewski model [7], [8] for the spin torque.

First, we investigate the influence of the thicknesses of the fixed layers on the magnetostatic exchange magnetic field in the plane of the free magnetic layer. The corresponding dependence is shown in Fig. 2. Each point is a result of statistical averaging with respect to 15 different realizations of the switching process. It demonstrates that the switching time from parallel to anti-parallel configuration and vice versa depends strongly on the fixed layer thickness. The most symmetric switching is achieved, when the fixed layer thickness is around 9-10nm. Surprisingly, the switching time at the symmetric switching point is shorter than in the case of an applied external compensating field [9]. This is due to the fact that by varying the thickness of the fixed layers one can only compensate the in-plane component of the magnetostatic exchange field. At the same time the field projection perpendicular to the plane is not compensated. The absolute value of the average field orthogonal to the plane of the free layer is also shown in Fig. 3. This field component makes the local magnetization in the free layer non-collinear to that in the fixed layers, which reduces the incubation delay and facilitates switching [10].

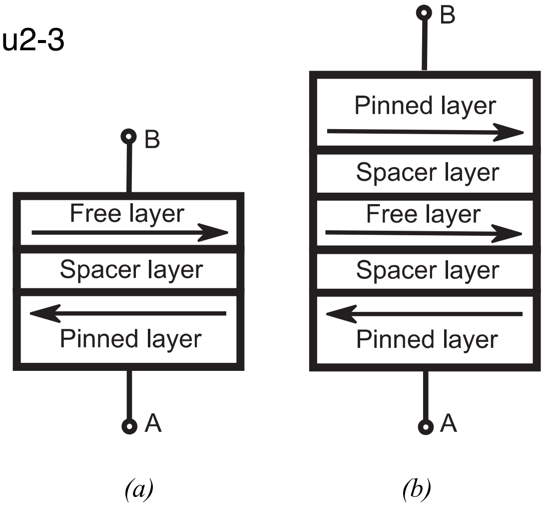
We now demonstrate that the switching time in a non-compensated penta-layer structure with anti-parallel orientation of the pinned layers can be further reduced by considering a composite free ferromagnetic layer without the central region.

Figure 4 illustrates the distribution of the magnetization in the free monolithic (a) and composite (b) layer after the relaxation according to the Landau-Lifshitz-Gilbert (LLG) equation by including the magnetostatic field h_{ms}. This field causes the magnetization 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 an enhanced spin transfer torque, when the current starts flowing [10], as was shown above. 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 5 demonstrates a substantial decrease of the switching time in the penta-layer 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 5nm, 15nm, and 20nm is shown in Fig.6. Due to the removal of the central region which represented the "bottleneck" for switching in the monolithic structure the potential barrier is decreased. At the same time the value of the potential barrier in the composite structure is still sufficiently high for guaranteeing the thermal stability (Fig. 6, Inset).

References

1. H.Zhao *et al.*, J. Appl. Phys. **109**, 07C720 (2011).
2. R.Sbiaa *et al.*, J. Appl. Phys. **109**, 07C707 (2011).
3. T. Devolder *et al.*, Appl. Phys. Lett. **86**, 062505 (2005).
4. G. Finocchio *et al.*, J. Appl. Phys. **99**, 08G5007 (2006).
5. P. Khalili Amiri et al., Appl. Phys. Lett. **99**, 112507 (2011).
6. G. D. Fuchs *et al.*, Appl. Phys. Lett. **86**, 152509 (2005).
7. J. Slonczewski, J. Magn. Magn. Mater. **159**, L1-L7 (1996).
8. J. Slonczewski, Phys. Rev. B, **71** 024411 (2005).
9. G. Finocchio *et. al.,* J. Appl. Phys. **101**, 063914 (2007).
10. A.D. Kent, Nature Materials **9**, 699 (2010).

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



(a) *(b)*

Fig. 1: *Schematic illustration of:*
(a) the three-layer MTJ; (b) the penta-layer MTJ.

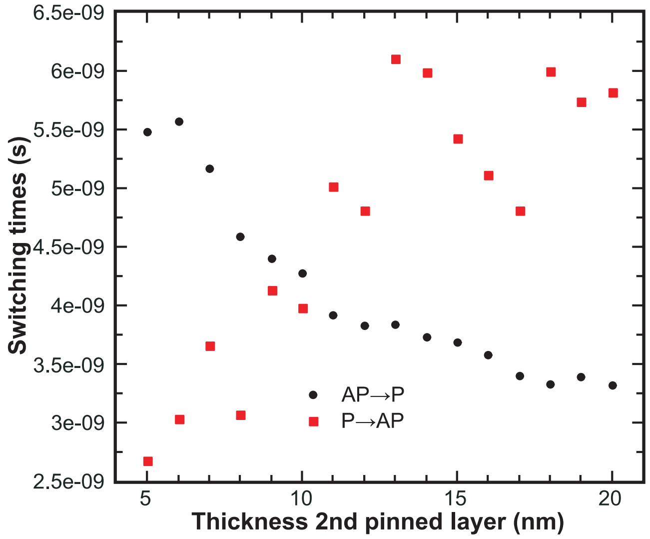


Fig. 2: *Dependence of the switching times between the two stable configurations on the thickness of the second fixed magnetic layer. The thickness of the first magnetic layer is 8nm.*

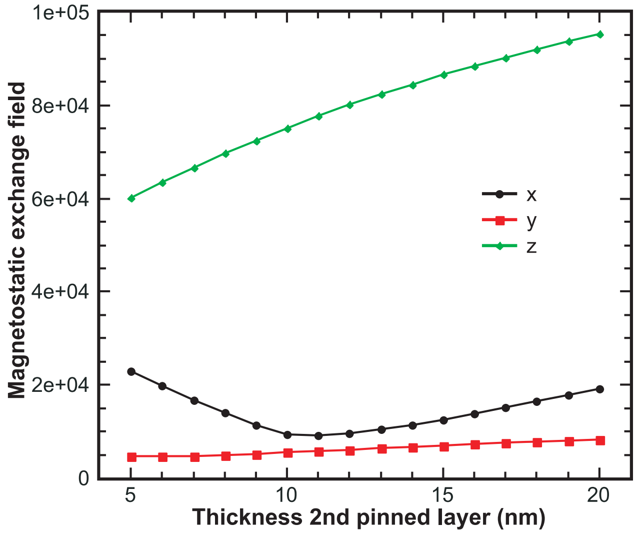
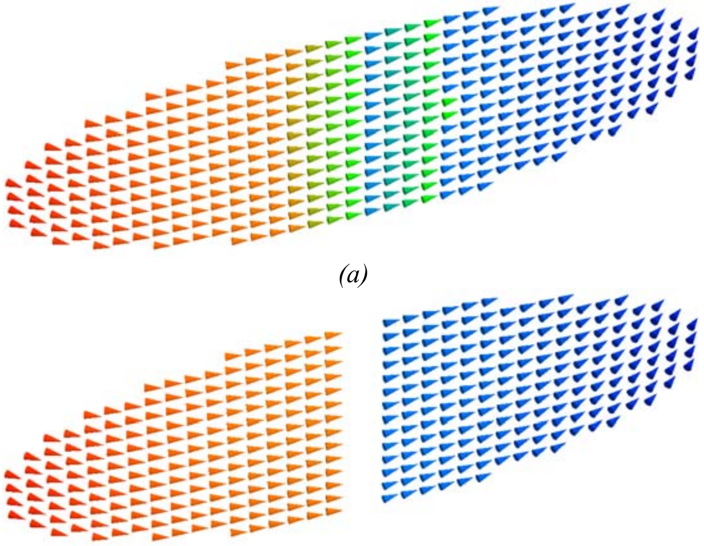


Fig. 3: *Dependence of the absolute values of different components of the averaged magnetostatic field acting on the free magnetic layer on the thickness of the second fixed magnetic layer. The thickness of the first magnetic layer is fixed at 8nm*



(a)

(b)

Fig. 4: *Snapshots of the initial magnetization:*
(a) monolithic free layer, (b) composite free layer.

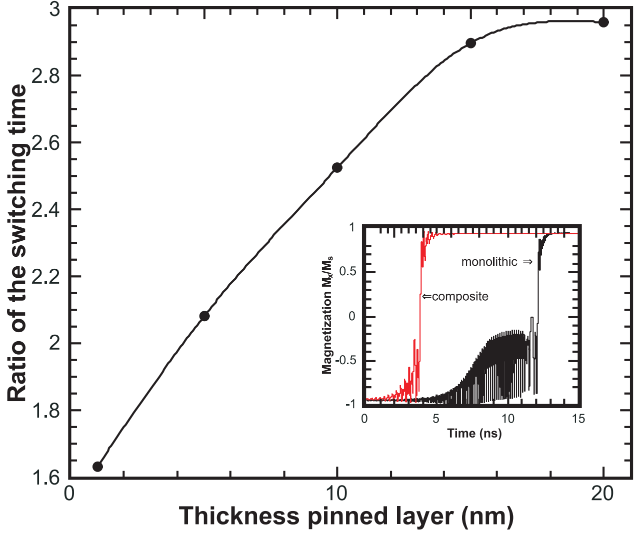


Fig. 5: *The ratio of the switching time in the monolithic structure vs. composite structure as the function of the thickness of the pinned layer. The inset shows the switching process for an MTJ with composite and monolithic free layer for a pinned layer thickness of 15nm.*

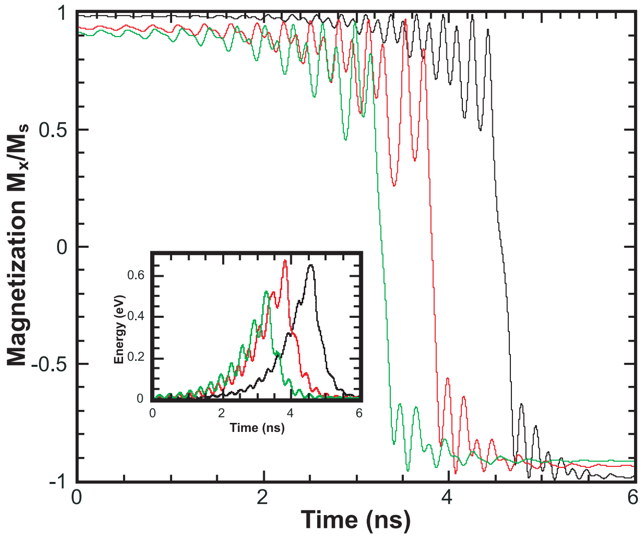


Fig. 6: *The switching process for MTJs with composite free layer for the pinned layer thicknesses of 5nm, 15nm, and 20nm (from right to left). The inset shows the evolution of the total energy of the free layer during the switching process.*