Transverse Domain Wall Formation in a Free Layer: A Mechanism for Switching Failure in a MTJ-based STT-MRAM

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***Abstract*— We investigate the switching failure probability in a MTJ-based STT-MRAM as a function of the switching current value and the pulse duration by means of extensive micromagnetic simulations. We analyze a new failure mechanism for switching through the formation and pinning of the transverse domain wall in the free layer of the STT-MRAM cell.**

Keywords—MTJ; micromagnetic modeling; STT-MRAM; switching probability; failure analysis

I. INTRODUCTION

Magnetoresistive random access memory with spin-transfer torque (STT-MRAM) is a promising candidate for future universal memory [1]. The basic element of an STT-MRAM is a pillar, a sandwich of two magnetic layers (Fig.1) separated by a non-magnetic metal (giant magnetoresistance (GMR) based devices) or a thin insulating oxide (magnetic tunnel junction (MTJ)). 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-transfer torque from the spin-polarized current flowing through the pillar. Depending on the orientation of the magnetizations the magnetic pillars can be divided into two categories: "in-plane" with magnetization lying in the plane of the magnetic layer and "perpendicular" with out-of-plane magnetization direction. The three-layer MTJ structure has been studied in detail including the issues of reliability and switching probability at different conditions [2-4]. At the same time the research on new materials and architectures for MTJ structures has recently intensified. A significant switching current density reduction in perpendicular MTJs and in-plane penta-layer MTJs (Fig.2) as compared to three-layer MTJs has been demonstrated [5].

In this work we investigate the switching probability of in-plane penta-layer MTJs for different switching current densities and pulse durations. We reveal a new switching failure mechanism through the formation and pinning of the transverse domain wall in the free layer of a penta-layer structure.

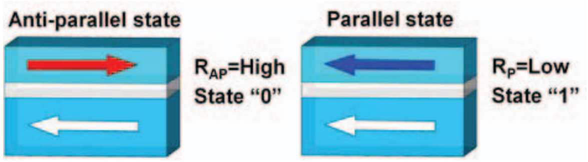

Fig. 1. Schematic illustration of a three-layer MTJ in a high resistance state (left) and low resistance state (right).

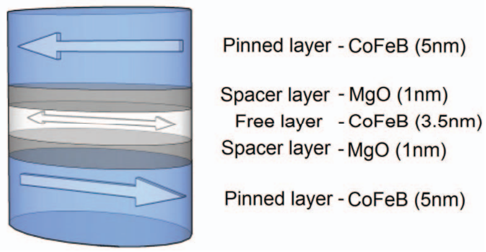

Fig. 2. Schematic illustration of a penta-layer MTJ.

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]:

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

Here, γ=2.3245·10^5m/(A·s) is the gyromagnetic ratio, α is the Gilbert damping parameter, μ_B is Bohr's magneton, j is the

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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. For the function $g(\theta)$ we use Slonczewski's expression for the MTJ with a dielectric layer [7]:

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

η is spin polarization factor, θ is an angle between the magnetization direction of the free layer and the pinned layer.

The local effective magnetic field is calculated as:

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

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.

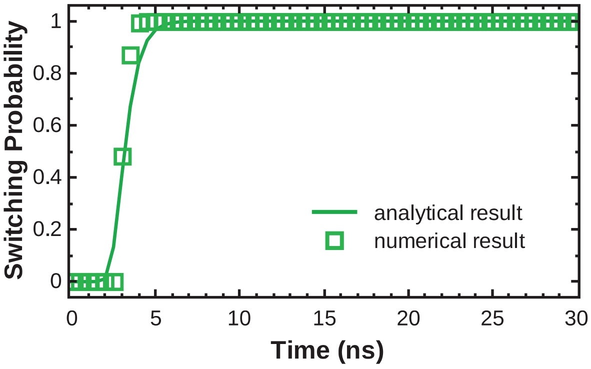

Fig. 3. Switching probability as a function of the pulse duration obtained from analytical solution (line) and numerical solution (symbols) for current density of $7.5 \cdot 10^6$A/cm^2. For switching probability estimation, 1000 simulations of switching were performed on each pulse width.

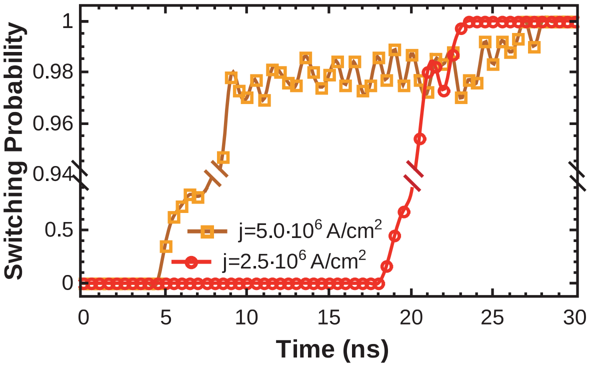

Fig. 4. Switching probability as a function of the pulse duration for current densities $2.5 \cdot 10^6$A/cm^2 and $5 \cdot 10^6$A/cm^2. For switching probability estimation, 1000 simulations of switching were performed on each pulse width.

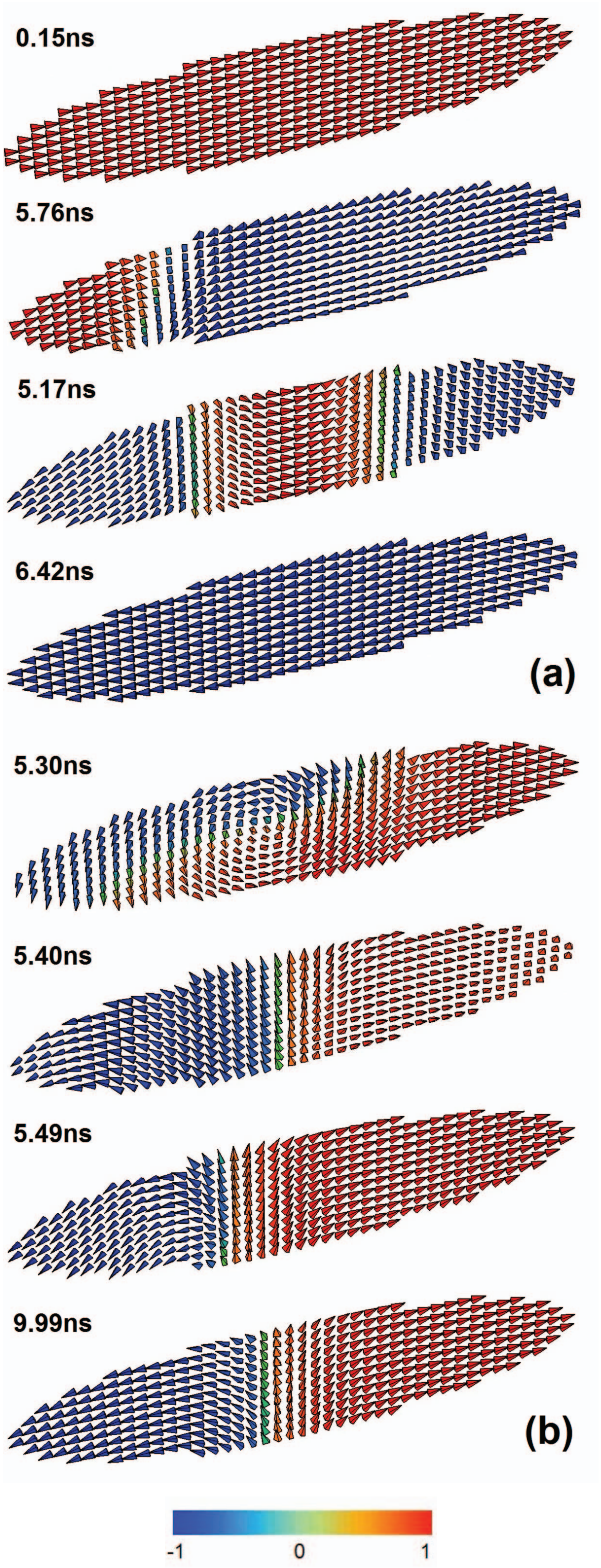

Fig. 5. Snapshots of the switching process for a penta-layer MTJ: (a) normal switching process; (b) with transverse domain wall formation. The direction of the magnetization is shown by unit vectors, the color indicates the value of the component in direction of the long axis.

III. RESULT AND DISCUSSION

The simulations are performed for a penta-layer nanopillar CoFeB(5nm)/ MgO(1nm)/ CoFeB(3.5nm)/ MgO(1nm)/ CoFeB(5nm) with an elliptical cross section 52.5×15nm^2 (Fig.2). The other model parameters are: T=300K, M_s=M_{sp}=8.9·10^{5}A/m, the exchange constant A=1·10^{-11}J/m, the crystalline anisotropy constant K=2·10^{3}J/m^3, the Gilbert damping parameter α=0.005, and the spin polarization factor η=0.63 [8].

First we have investigated the dependence of the switching statistics on the current density and pulse duration (Fig.3, Fig.4). For that purpose we have simulated 100 switching cycles under the current density 2.5·10^{6}A/cm^2, 5·10^{6}A/cm^2, and 7.5·10^{6}A/cm^2 and a time pulse 30ns. We took the state of the system at the time intervals multiple of 0.5ns, and for each of these states we computed 10 relaxation processes under the influence of temperature. This gave us 1000 simulation realizations of the switching process for each pulse duration (multiple of 0.5ns) and for each of the three values of the current density for switching probability evaluation.

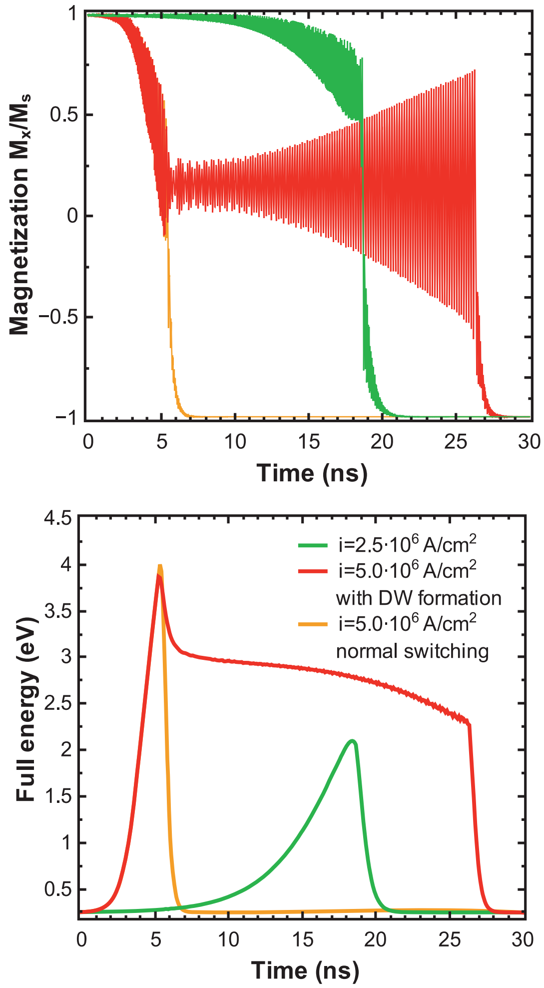

Fig. 6. Averaged magnetization component in direction of the long axis (top) and full energy (bottom) as function of time.

Fig.3 shows that for a current density 7.5·10^{6}A/cm^2 our numerical solution is in good agreement with the analytical expression:

$$P(t_p) = \exp\left(-\Delta \cdot \sin^2 \varphi\right) \tag{4}$$

Here, t_p is duration of the current pulse, Δ is the thermal stability factor. We used for φ the equation from [10]:

$$\varphi = \frac{\pi}{2}\exp\left(-\frac{\eta\mu_B}{eM_s d}(j-j_c)\cdot t_p\right) \tag{5}$$

Here, η is spin polarization factor, μ_B is Bohr's magneton, e is the electron charge, M_s is the saturation magnetizations, d is the thickness of the free layer, j is the current density, j_c is the critical current density.

Next we found that the switching probability for the current density 5·10^6 A/cm^2 is equal to one for which the pulse is longer than 26.5ns. This pulse duration is longer than the respective value of 23ns needed to achieve the ultimate switching at the current density 2.5·10^6 A/cm^2 (Fig.4). Interestingly, for the current density 5·10^6 A/cm^2 and a pulse duration between 8ns and 26.5ns the switching probability is less than one and fluctuates. This is in striking contrast to the earlier results, where the increasing pulse duration and current density always leaded to the switching probability increase [3]. To determine the reason for this discrepancy, we have considered the switching process in detail (Fig.5). We found that during some of the switching realizations at the current density 5·10^6 A/cm^2 a vortex is created (Fig5b, 5.3ns). The formation of the vortex state in films thicker than 3.2nm is fully consistent with the results obtained previously for three-layer structures with a synthetic free layer [9]. Later the vortex transforms into a transverse domain wall (Fig.5b, 5.4ns). After that the transverse wall starts oscillating around the center of the free layer with an increasing amplitude (Fig.6, top), which leads to the increase of the switching time. We note that at a lower current density the domain wall is not formed and the switching proceeds normally (Fig.5a). The formation of the transverse domain wall is possible at higher currents, when the switching energy barrier for normal switching is practically equal to the formation energy barrier of the vortex/transverse domain wall state (Fig.6, bottom).

Now we investigate the validity of the criterion typically used to describe the 100% switching. As illustrated in Fig.7, in the case of normal switching from 1 to -1 the switching probability equals to 1 if the normalized average magnetization M_x/M_s along the long axis becomes less than -0.5 (M_x/M_s < -0.5) [3]. If, however, the vortex state is generated, due to the oscillatory behavior of the domain wall the 100% switching can be achieved even when $M_x/M_s > 0.5$ (Fig.8). This exception demonstrates that in making a decision about reliable switching one has to consider not only the average magnetization but also the state of the system during switching.

IV. CONCLUSION

In this work we have investigated the switching statistics in penta-layer MTJs. Our extensive simulations show that under certain conditions there is a non-negligible probability of the formation of a vortex state/transverse domain wall during switching. This results in drastic increase in the switching time or can even lead to a complete switching failure. The detected switching failure mechanism must be taken into account in realistic performance optimization of STT-MRAM devices.

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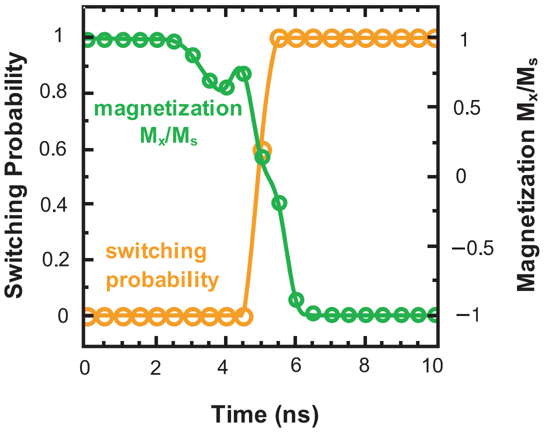

Fig. 7. Switching probability vs. averaged magnetization component in the direction of the long axis as a function of time for normal switching.

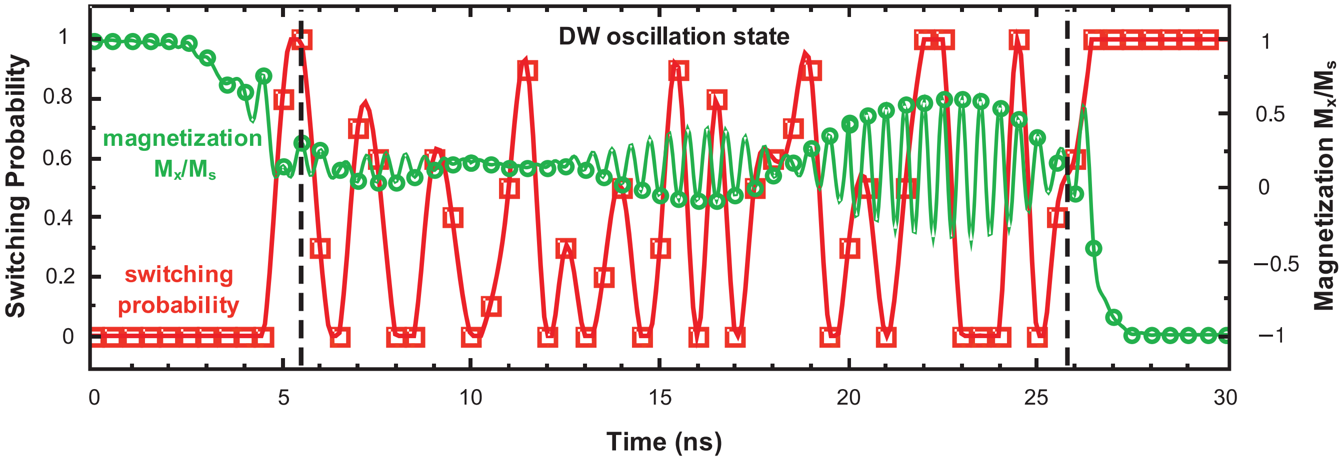

Fig. 8. Switching probability vs. averaged magnetization component in the direction of the long axis as a function of time for switching with formation of the transverse domain wall.