Micromagnetic modeling of high-resistance magnetic tunnel junctions including the effect of non-uniform current distribution

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Introduction

- Nanoscale time-resolved images of the magnetization dynamics induced by spin torque have shown inhomogeneous magnetization spatial configurations. (Y. Acremann et al.; PRL 96, 217202; 2006)

- Full micromagnetic modeling is necessary in order to describe accurately the magnetization reversal mechanisms. (L. Torres et al.; JMMM 286, 381; 2005)

- During the spin-torque-driven process, the resistance of the nanostructure changes according to the magnetization spatial configuration.

- Therefore, the current distribution changes as well. These effects on the magnetization reversal are studied here.

Geometry and Non-uniform Current Distribution Model

- Landau-Lifshitz-Gilbert with Slonczewski spin-torque term.

$$\left(1+\alpha^2\right)\frac{d\vec{m}}{d\tau}=-\vec{m}\times\vec{h}_{eff}-\alpha\,\vec{m}\times\left(\vec{m}\times\vec{h}_{eff}\right)-\frac{g\mu_B J}{L_z\gamma_0 M_s^2 e}\,g_T\left(\vec{m},\vec{p}\right)\left(\vec{m}\times\left(\vec{m}\times\vec{p}\right)-\alpha\,\vec{m}\times\vec{p}\right)$$

where;

$\alpha = 0{,}01$ $\qquad d\tau = \gamma_0 M_s dt$

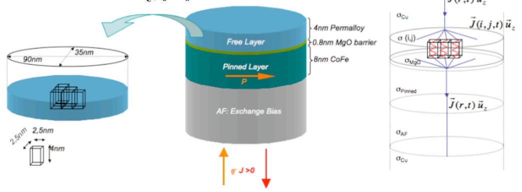
and;

$$g_T\left(\vec{m},\vec{p}\right)=0{,}5\,\eta_T\left[1+\eta_T^2\cos(\theta)\right]^{-1}$$

$\eta_T = 0.7$

$M_S = 6{,}45\times10^6 \quad (A/m)$

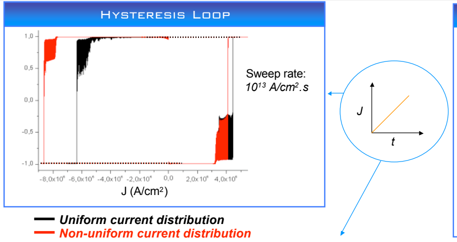
$A = 1{,}3\times10^{-11} \quad (J/m)$



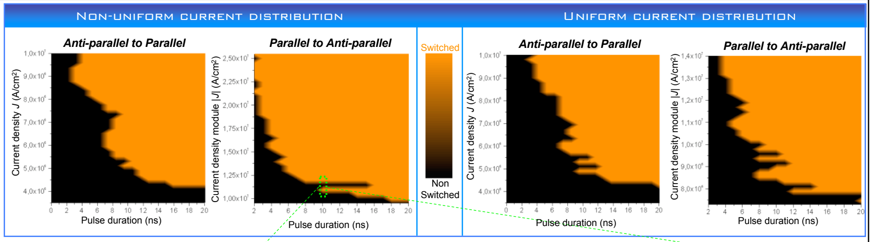
- The non-uniform current distribution considers that each computational cell has a resistance *r(i,j,t)* which varies according to the relative orientation between its magnetization and that of the corresponding cell in the pinned layer.

Deterministic Simulation *T=0K*

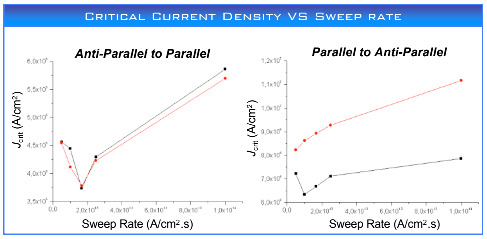
Hysteresis Loop

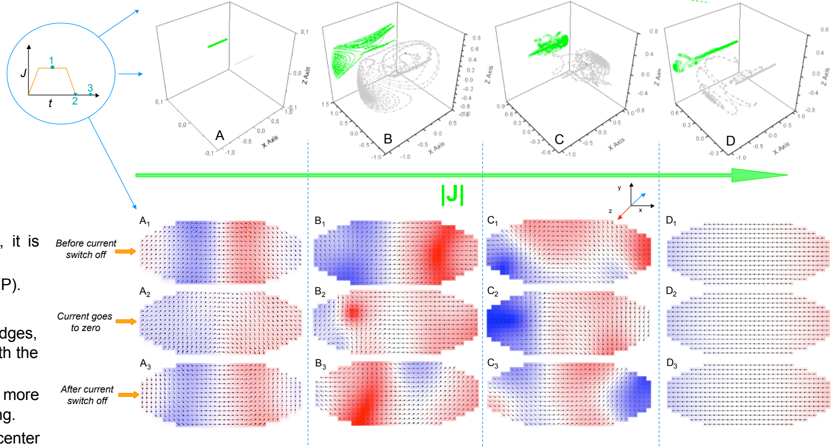


Non-uniform current distribution / Uniform current distribution



Critical Current Density VS Sweep rate

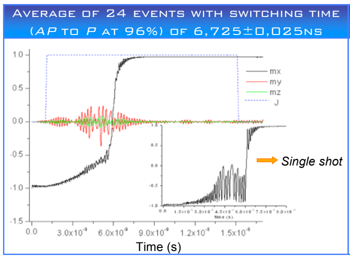




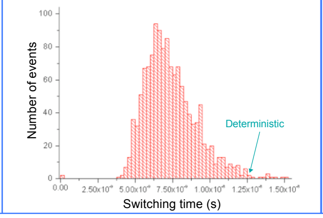
- By comparing the different critical switching density currents (J_{crit}), it is verified that regarding the non-uniform current distribution model;
  - It favors switching going from the anti-parallel (AP) to parallel state (P).
  - It hinders the parallel (P) to anti-parallel (AP) state reversal.
- The magnetization oscillations leading to the switching begin at the edges, mainly due to the normal component of the magnetostatic coupling with the fixed layer, then:
  - In the AP→P reversal, resistance lowers in the edges first, thus more current rushes there promoting oscillations and triggering the switching.
  - In the P→AP case the opposite occurs going more current to the center of the sample delaying the switching.

Stochastic Simulation *T=411K*

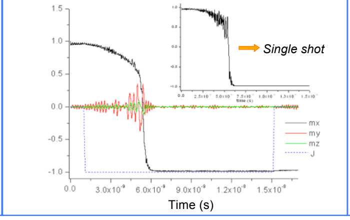
Average of 24 events with switching time (*AP to P* at 96%) of 6,725±0,025ns



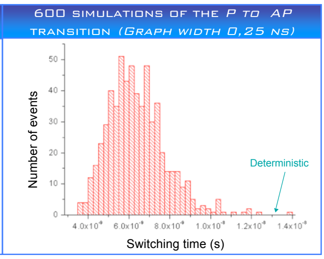
1200 simulations of the *AP to P* transition *(graph width 0,25 ns)*



Average of 12 events with switching time (*P to AP* at 96%) of 5,825±0,025ns



600 simulations of the *P to AP* transition *(graph width 0,25 ns)*



$J_{AP\text{-}P}$ = 4,50x10⁶ A/cm² $\quad t_{pulse}$ = 14ns

$J_{P\text{-}AP}$ = 1,05x10⁷ A/cm² $\quad t_{pulse}$ = 14ns

Summary

- In the deterministic computations, the non-uniform current distribution model yields less erratic critical transition curves than the uniform distribution one.

- Stochastic simulations reveal that the transition is rather uniform, with only minor oscillations due to thermal fluctuations. Taking a look at the average magnetization dynamics during the switch, one can see a smooth transition with the formation of *C state* before and after the switch. (G. Finocchio et al.; JAP 101, 063914; 2007)

- Comparing the stochastic simulations with the deterministic case, one can see that thermal activation clearly promotes the switching event.

- Although the proposed model still needs to be tested directly with experimental data, it is believed that it allows for more realistic simulations, specially when thermal activation is considered as well.