Simulation of Spin-Torque and Magnetization Dynamics in STT-MRAM Multi-Level Cells

Mario Bendra[1,2], Simone Fiorentini[1,2], Siegfried Selberherr[2], Wolfgang Goes[3], Viktor Sverdlov[1,2]

[1] *Christian Doppler Laboratory for Nonvolatile Magnetoresistive Memory and Logic at the*
[2] *Institute for Microelectronics, TU Wien, Gußhausstraße 27-29, A-1040 Wien, Austria*
[3] *Silvaco Europe Ltd., Compass Point, St Ives, Cambridge, PE27 5JL, United Kingdom*

The development of advanced magnetic tunnel junctions with a footprint in the single-digit nanometer range can be achieved using structures with an elongated and composite ferromagnetic free layer. We present a recently developed [1] fully three-dimensional finite element method based modeling and simulation approach which includes all relevant physical phenomena, responsible for proper ultra-scaled MRAM cells. The coupled spin and charge drift-diffusion (DD) method accurately describes the charge and the spin transport through a nanometer-sized magnetic valve. We extended the method to magnetic tunnel junctions (MTJs) by modeling the tunnel barrier (TB) as a poor conductor with a local conductivity depending on the relative orientation of the magnetization. The DD approach is supplemented with appropriate boundary conditions for the spin current $\mathbf{J_S^{TB}}$ at the TB interfaces to account for the dependence of the torque on the relative magnetization orientation specific to MTJs [1]:

$$\mathbf{J_S^{TB}} = -\frac{\mu_B}{e}\frac{\mathbf{J_C^{TB}}\cdot\mathbf{n}}{1+P_{RL}P_{FL}\mathbf{m_{RL}}\cdot\mathbf{m_{FL}}}\left[P_{RL}\mathbf{m_{RL}} + P_{FL}\mathbf{m_{FL}} + {}^{1}\!/_{2}(P^{\eta}_{RL}P_{RL} - P^{\eta}_{FL}P_{FL})\mathbf{m_{RL}}\times\mathbf{m_{FL}}\right] \tag{1}$$

$\mathbf{J_C^{TB}}$ is the electric current density at the interface, $\mathbf{n}$ is the interface normal, $\mathbf{m_{RL(FL)}}$ is the magnetization of the reference layer (RL) and free layer (FL), $P_{RL(FL)}$ are in-plane Slonczewski polarization parameters, P^{η}_{RL} and P^{η}_{FL} are out-of-plane polarization parameters, μ_B is the Bohr magneton, and e is the elementary charge. The boundary condition (1) is key to evaluate the spin currents and the spin accumulations in the RL and the FL. Employing (1) gives the opportunity to describe the spin and charge transport coupled to the magnetization in arbitrary stacks of MTJs and metallic spin valves with a unified DD approach. This approach allows the proper analysis of the sequential switching of a FL consisting of two ferromagnetic pieces FL$_1$ and FL$_2$ separated by a tunnel junction (Fig. 1). After inverting the FL from parallel to anti-parallel configuration we observed a back hopping of FL$_1$ and then FL$_2$ at higher current densities. This phenomenon is similar to the unwanted back-hopping of the reference layer [2]. The case of the composite FL the back hopping results in a multi-bit cell with four distinctly different states shown in Fig. 1.

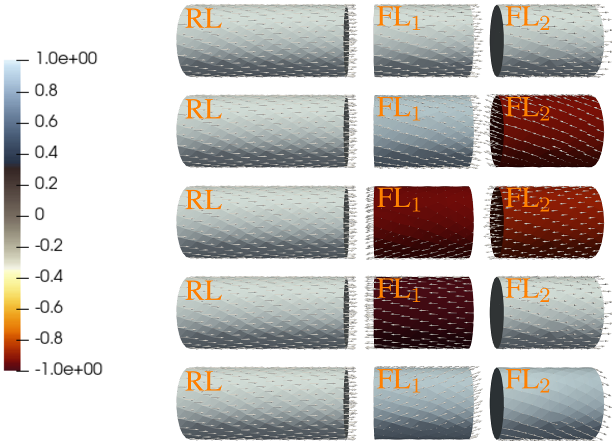

Figure 1: Switching snapshots in the following order: Initial, intermediate, and final state, for the configuration P to AP. Arrows indicate the magnetization directions, and the color-coding represents the average magnetization in x-direction.

References

[1] S. Fiorentini, et al.: Spin and charge drift-diffusion in ultra-scaled MRAM cells. Sci. Rep., 12, 20958 (2022).

[2] C. Abert, et al.: Back-hopping in spin-transfer-torque devices: Possible origin and countermeasures. Phys. Rev. App., 9, 054010 (2018).