Comparing Spice Model of STT based MTJ with Micromagnetic Simulations

Paulo R. Klaudat and Raphael M. Brum
Department of Electrical Engineering
Federal University of Rio Grande do Sul
Porto Alegre, Brazil
pauloklaudat@ieee.org

***Abstract*—The development of Spice models is an important tool to explore all the potential of spin-transfer torque MRAM in simulations. However promote the compatibility of Micromagnetic behavior with Spice simulations is a great challenge. In this work, we analyze a Spice MTJ model built in a approach to solve the LLG equation with a MTJ model description to Micromagnetic simulations in terms of the dynamic spin motion. We ported the Spice model to the Cadence platform and performed experiments to assess the proximity of the Magnetization behavior in terms of results. We show that the Spectre ports work successfully and the models are compatible.**

I. Introduction

The elementary Magnetoresistive Random Access Memory (MRAM) is made by one transistor and a Magnetic Tunnel Junction (MTJ). This memory has a great characteristics such as high reading speed, high endurance, large retention time and non-volatility. The MTJ is responsible to restore the data using a defined resistance value that can be written using different approaches, one of them is called Spin Transfer Torque (STT), of which the magnitude of resistance can be changed applying a current through the junction.

One of the biggest problems to simulate MRAM metrics is the compatibility with micromagnetic behavior in MTJ and the common Circuits Simulators such as Synopsys Hspice and Cadence Spectre. Many Spice models of MTJ have been reported using different approaches, such as finite-state machine [1] or a Verilog-A [2] behavioral description, all models aforementioned do not represent the spin dynamic portrayed by Landau- Lifshitz-Gilbert (LLG) Equation (3), which is significantly when we need to measure the power consumption of an MRAM array or the time to change the bit value.

In this work, we ported a Spice Model of STT-MTJ [3] that captures the spin dynamics to Cadence Spectre Syntax and compare with Micromagnetic Simulations of MTJ using Mumax3 Tool. We simulate these models in terms of parameters compatibility in order to measure the differences in results.

This paper is structured as follows: Section II provides a brief explanation of STT-MTJ, detailing this structure and the STT technology as a mechanism to write in the junction. The third and fourth sections will be presented the Spice Model and Mumax3 Tool. In the last section, these models will be compared in terms of the Magnetization trajectory and the relation between the solution of LLG and the resistance variation.

II. Magnetic Tunnel Junctions

MTJs are spintronic devices common made of two stacks of ferromagnetic layers separated by a insulator [4] as shown in Fig. 1.

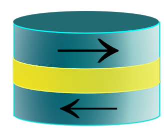

Fig. 1. Magnetic Tunnel Junction

One of the layers has a coercitive magnetic field, which keeps the Magnetization orientation, whereas in the other ferromagnetic layer the Magnetization has a free orientation that can be changed by an external field. The two possible arrangements, relative to a fixed layer, are called Anti-parallel state ($\theta = 0$) and Parallel state ($\theta = \pi$) correspond respectively to a high resistance ($\mathrm{R_{ap}}$) and low resistance ($\mathrm{R_p}$).

Upon the application of electric field between the ferromagnetic layers, electrons can tunnel through the insulator. Depending on the orientation of electron, it is called Spin Up or Spin Down electron and each one has different probabilities of tunneling through the barrier. This effect is a quantum phenomena known as *Tunneling Magnetoresistance (TMR)*. Commonly, this effect is used as a ratio and, from that, it is possible to measure the quality of MTJ by the following expression:

$$TMR = \frac{\Delta R}{R_p} = \frac{R_{ap} - R_p}{R_p} \tag{1}$$

In 1989 Slonczewski proposed a model, which was incorporated in LLG equation in STT term, that relates the conductance to the magnetization angle θ:

$$G(\theta) = G_0(1 + P^2 \cos\theta) \tag{2}$$

where the constants G_0 and P are related to the properties of the ferromagnetic layers and the quality of the barrier. [5]

In MTJs based in STT technology, spin polarized electrons exert a spin torque to the layers and can induce a magnetization switching, which is described by LLG Equation term (4). In STT-MTJ, if the current is larger than current commonly called critical current, the free layer changes his orientation and switches the MTJ state.

As aforementioned, there are others possibilities to change the state, the thermal instability also can randomly flip the magnetization direction, which some times is not intended. In contrast, we can improve the junction stability increasing the thickness and aspect ratio. However, changing the structure dimensions will have an impact in others parameters, such as write power consumption.

III. LLG Spice MTJ Model

In this model [3] MTJ is a box composed by modules of subcircuits as shown in Fig. 2 that emulates each feature of the junction using basic circuits elements. The center of this model is the STT module, which calculates the LLG equation considering a single domain.

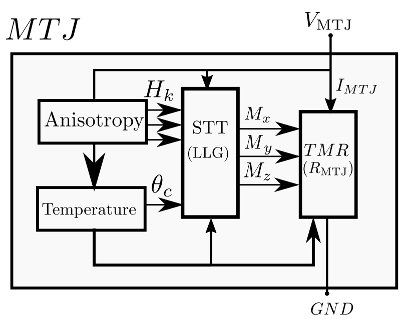

Fig. 2. Macro Spice Model modules

A. STT module and the LLG equation

The Landau-Lifshitz-Gilbert equation (LLG), as shown:

$$\frac{1+\alpha^2}{\gamma}\cdot\frac{d\vec{M}}{dt} = -(\vec{M}\times\vec{H_{\mathrm{eff}}}) - \alpha(\vec{M}\times(\vec{M}\times\vec{H_{\mathrm{eff}}})) - \frac{\hbar j}{eM_s d}G(\theta)(\vec{M}\times\vec{M}\times\vec{p}) \tag{3}$$

represents the Magnetization as a time-dependent vector $\vec{M}$. The terms on the right side of the equation are divided in three important parts of spin dynamics: the motion of precession, damping and STT.

$$\frac{\hbar j}{eM_s d}G(\theta)(\vec{M}\times\vec{M}\times\vec{p}) \quad \rightarrow \mathrm{STT} \tag{4}$$

$$\vec{M}\times\vec{H_{\mathrm{eff}}} \quad \rightarrow \mathrm{Precession} \tag{5}$$

$$\alpha(\vec{M}\times(\vec{M}\times\vec{H_{\mathrm{eff}}})) \quad \rightarrow \mathrm{Damping} \tag{6}$$

The H_{eff} or H_k represents the effective magnetic field applied to ferromagnetic layer, where α is the Gilbert damping parameter , γ is the gyromagnetic ratio, $\hbar$ is the reduced Planck constant, j is the current density, e is the electron charge, d is the free layer thickness and $G(\theta)$ is the conductance function and p is the STT component.

The position of $\vec{M}$ and H_{eff} are fed into the STT module, which implements Eq. (3) into three components $\vec{M}_x$, $\vec{M}_y$ and $\vec{M}_z$ with non-linear current sources as shown in Fig. 3 . The voltage in capacitor corresponds the derivative term of LLG and his capacitance reflects the relation of Gilbert Damping factor and the gyromagnetic ratio. Each current source represents one of the important terms of LLG previously mentioned. The additional node in circuit sets the initial angle considering the consecutive switching. Through the capacitor voltage the module outputs the x,y and z components of the magnetization.

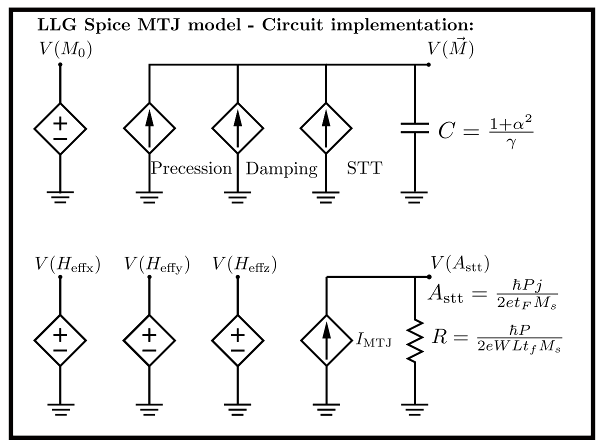

Fig. 3. LLG Spice MTJ model [3]

B. TMR module

The subcircuit is responsible for converting the instantaneous magnetization $\vec{M}$ to spherical coordinates, which makes it easier to calculate the relative angle between fixed and free layer and determine the MTJ resistance in parallel state according to Eq. (1).

Such as mentioned, the temperature has a great influence in the time switching, whereas the relationship in this model can be described by TMR in function of the bias voltage and Temperature, as expressed in following equation:

$$\mathrm{TMR}(T,V) = \frac{2P_o^2(1-\alpha_{sp}T^{3/2})^2}{(1-P_o^2(1-\alpha_{sp}T^{3/2})^2)(1+(V/V_0)^2)} \tag{7}$$

where T is the absolute temperature, α_{sp} is a material-dependent constant, P_0 is the polarization factor at absolute zero temperature and V_0 is a fitting parameter.

C. Shape and Temperature module

While the Shape anisotropy module calculates H_{eff} from the initial parameters and the bias conditions, the Temperature subcircuit calculates the initial critical angle used to determine the probability of flipping the resistance state. This effect is made by a RC line circuit model to emulate the Heat Diffusion through the junction. Both subcircuits send parameters to LLG subcircuit to solve the LLG equation.

At long current pulses, the internal temperature of MTJ and the probability of switching increases by heat diffusion. This model calculates this probability in terms of the initial critical angle as follows:

$$P_{sw} = 1 - \int_0^{\theta_c} \frac{\sin\theta \exp\left(-\Delta \sin^2\theta\right)}{\int_0^{\frac{\pi}{2}} \sin\theta \exp\left(-\Delta \sin^2\theta\right) d\theta} d\theta, \quad (8)$$

The thermal stability factor is portrayed by the following expression: $\Delta = E_b/k_b T$, where E is the energy barrier of the MTJ, that is, the energy necessary to pass the potential barrier and change the Magnetization orientation. k_b is the Boltzmann constant and T is the temperature.

IV. Micromagnetic Simulations with Mumax3

In the case of micro and nano layers of ferromagnetic material, the Magnetization is commonly described as a continuum field $\vec{M}(r,t)$, which is the solution of the LLG equation. Mumax3 [6] is an open-source software and it calculates the space and time-dependent magnetization dynamics in micro or nano ferromagnetic layers using a finite-difference discretization.

This is made by separating the regions in cells, where the Magnetization is described by:

$$\begin{aligned}\frac{\partial M(r,t)}{\partial t} =& -\frac{\gamma}{1+\alpha^2} M(r,t) \times H_{\text{eff}}(r,t) \\ & - \frac{\alpha\gamma}{M_s(1+\alpha^2)} M(r,t) \times \left(M(r,t) \times H_{\text{eff}}(r,t)\right)\end{aligned} \quad (9)$$

Mumax3 features a series of standard problems in nano and micro ferromagnetic materials, which was implemented in a language based in GO and CUDA.

A. Slonczewski Standard Problem

This problem refers to a STT-MTJ structure, considering two layers of same ferromagnetic material separated by an barrier. The Magnetization vector is then calculated in only one layer, which has the free Magnetization orientation.

Mumax3 solves the LLG by treating the Magnetization in center of each cell and returns the spin motion and the three axis of the Magnetization Vector in function of time. It is important to emphasize that each cell is separated in 2D or 3D grid to calculate in finite terms of discrete form.

B. Shape and Geometry

Such as mentioned, each cell composes a layer structure, which can have different shapes as: Ellipse, Cylinder, Square and others. This Geometry is important when we consider that the effective field (H_{eff}) is calculated using a Fast Fourier Transform (FFT) and, consequently the spatial discretization is made into equal cuboid cells, which is suited to rectangular geometries.

The Slonczewski problem like the Spice MTJ model [3], uses the geometry and dimensions to determine the junction resistance.

C. Slonczewski Spin-Transfer Torque

Mumax3 uses the Landau-Lifshitz term of STT to promote the spin motion based in following equation:

$$\vec{\tau}_{SL} = \beta\frac{\epsilon - \alpha\epsilon'}{1+\alpha^2}(\vec{m} \times (\vec{mp} \times \vec{m})) - \beta\frac{\epsilon' - \alpha\epsilon}{1+\alpha^2}\vec{m} \times \vec{mp} \quad (10)$$

$$\beta = \frac{j_z \hbar}{M_{sat} e d} \quad (11)$$

Where j_z is current along the z axis, d is the free layer thickness, $\vec{mp}$ is the fixed-layer magnetization, α is the Landau-Lifshitz damping constant and M_{sat} is the Magnetization saturation.

V. Simulation Results

Transient simulations were performed over the two presented models in terms of parameters compatibility, these parameters are described in Table I in order to compare the Spice model with Micromagnetic simulation.

TABLE I
Compatible Parameters

Parameter	Description	Value
Lx	Free Layer Width	160 [nm]
Ly	Free Layer Length	80 [nm]
Lz	Free Layer thickness	5 [nm]
M_{sat}	Saturation Magnetization	800 [kA/m]
I_{MTJ}	Switching current	0.008 [A]
P	Polarization factor	0.5669
α	Landau-Lifshitz Damping factor	0.01
-	Shape	Elliptical

The Fig. 4 to 6 refer to the solution of LLG equation for each model: the Mumax3 Sloncweszki problem and the LLG Spice MTJ model, respectively. The variations in each component are different, because the Magnetization is more susceptible to align with the magnetic field in the easy-axis direction.

Whereas the M_x and M_z have brief oscillations around the same points and return to initial state after switching. M_y changes the direction, as observable in Fig. 5. It occurs, because M_y is the easy axis of Magnetization, the axis that after switching state turns to the diametrically opposite direction ($\theta = 0$ to $\theta = \pi$) or vice versa. The easy axis represents the current in the junction, when the MTJ assumes a different state the current magnitude will not be equal.

An important factor to consider is the spin motion during the switching state time trajectory, the Fig. 7 represents the dynamic of spin while turning the direction orientation. All characteristics of LLG present in both simulations, such as the precession and damping movement are explicit, note that the Magnetization accomplishes a rotational trajectory (Precession) around a point and all curves are damped until the end point.

It is important to emphasize that all simulations were performed considering a single domain in the free layer of MTJ, because the Macro Spice model does not allow to increase the number of domains, which is possible in the Micromagnetic simulation.

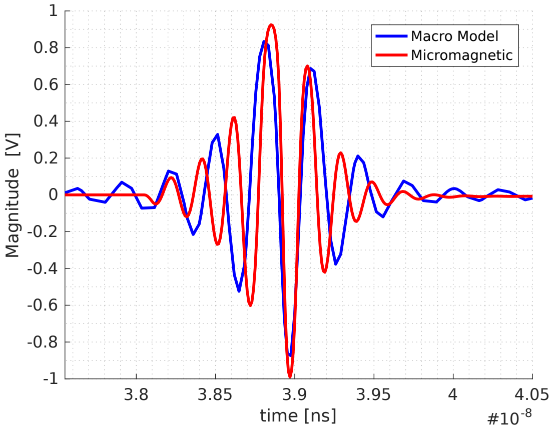

Fig. 4. Magnetization M_x

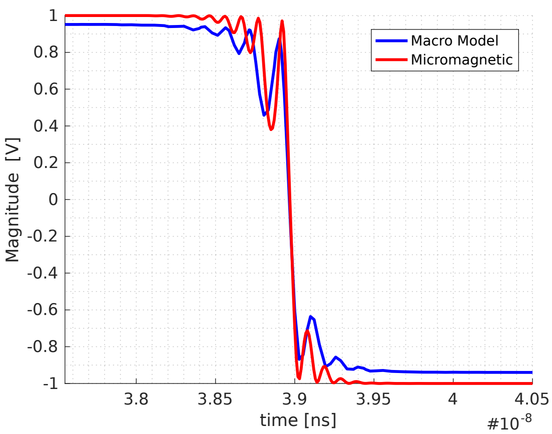

Fig. 5. Magnetization M_y

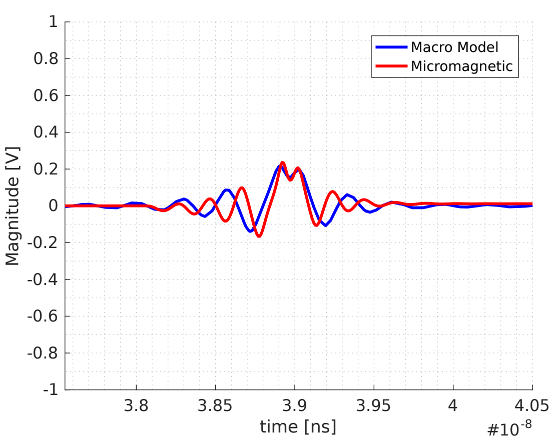

Fig. 6. Magnetization M_z

VI. Conclusion

The Micromagnetic simulation in this field represents the Gold Standard in terms of accuracy to solve the Magnetization behavior in ferromagnetic layers. In contrast, the Macro Spice

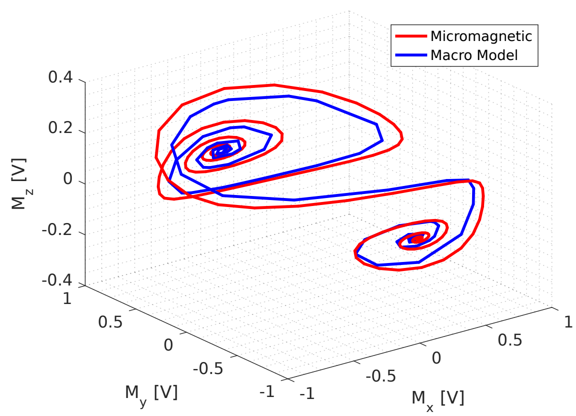

Fig. 7. Magnetization Trajectory

Model promotes the same behavior and great proximity in terms of results with fewer electrical simulation consumption.

Both models worked as expected and, noticeably, the LLG Spice MTJ model has the same behavior in terms of compatibility with Micromagnetic simulations and portrayed all terms of LLG equation. It allows to simulate metrics of MRAM such as power consumption and time to switching with great proximity in terms of results.

We conclude that, for a single domain, the Macro Spice Model has a great proximity in terms of results and emulating the MTJ behavior, as can see in Fig. 7 the Magnetization Trajectory is the same in all simulations with all user configurable parameters.

Acknowledgment

The authors would like to acknowledge the support of the Brazilian National Council for Scientific and Technological Development (CNPq) and FAPERGS through the PRONEX SISCHIP2 scientific project.

References

[1] W. Zhao, E. Belhaire, Q. Mistral, C. Chappert, V. Javerliac, B. Dieny, and E. Nicolle, "Macro-model of spin-transfer torque based magnetic tunnel junction device for hybrid magnetic-cmos design," in *Behavioral Modeling and Simulation Workshop, Proceedings of the 2006 IEEE International*. IEEE, 2006, pp. 40–43.

[2] Y. Wang, H. Cai, L. A. de Barros Naviner, Y. Zhang, X. Zhao, E. Deng, J.-O. Klein, and W. Zhao, "Compact model of dielectric breakdown in spin-transfer torque magnetic tunnel junction," *IEEE Transactions on Electron Devices*, vol. 63, no. 4, pp. 1762–1767, 2016.

[3] J. Kim, A. Chen, B. Behin-Aein, S. Kumar, J.-P. Wang, and C. H. Kim, "A technology-agnostic mtj spice model with user-defined dimensions for stt-mram scalability studies," in *2015 IEEE custom integrated circuits conference (CICC)*. IEEE, 2015, pp. 1–4.

[4] R. M. Brum and G. I. Wirth, "Magpdk: An open-source process design kit for circuit design with magnetic tunnel junctions," in *Integrated Circuits and Systems Design (SBCCI), 2016 29th Symposium on*. IEEE, 2016, pp. 1–6.

[5] S. Yuasa and D. Djayaprawira, "Giant tunnel magnetoresistance in magnetic tunnel junctions with a crystalline mgo (0 0 1) barrier," *Journal of Physics D: Applied Physics*, vol. 40, no. 21, p. R337, 2007.

[6] A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, F. Garcia-Sanchez, and B. Van Waeyenberge, "The design and verification of mumax3," *AIP advances*, vol. 4, no. 10, p. 107133, 2014.