Monte-Carlo Simulations of Magnetic Tunnel Junctions : from Physics to Application

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INTRODUCTION

Magnetic Tunnel Junctions (MTJs) – the basic structures of the Spin-Transfer Torque Magnetic RAMs (STT-MRAM) currently reaching the market - present a complex and probabilistic switching behavior. Although some analytical models describing this behavior exist, they can not describe all the switching regimes of the MTJs. They can model low ("subcritical") and high ("supercritical") currents, but not the intermediate currents, which are essential for applications.

In this work, we present Monte-Carlo simulations of MTJs that have been used to build a compact model linking the two different current regimes. This model allowed us to perform system-level simulations of an original neuroinspired chip that uses MTJs as binary stochastic "synapses".

ABOUT OUR SIMULATOR OF MTJS

Figure 1 presents a typical MTJ. We studied current-driven devices: a tunnel current goes through the MTJ and favours one of the two stable magnetic states thanks to spin-transfer torque (STT).

Due to the small dimensions of the free layer, we considered its total magnetic moment as a unique *macrospin* $\mathbf{m_f}$. We simulated its dynamic thanks to the usual Landau-Lifschitz-Gilbert equation (in SI units), augmented of two field-like terms: a Slonczewski's one - $\mathbf{H_{STT}}$ - for the STT part [1] and a stochastic term $\mathbf{h_{sto}}$ to include the thermal agitation of $\mathbf{m_f}$:

$$\frac{(1+\alpha^2)}{|\gamma|}\frac{\mathrm{d}\mathbf{m_f}}{\mathrm{d}t} = -\mu_0 \mathbf{m_f} \times (\mathbf{H_{eff}} + \mathbf{h_{sto}}) - \frac{\alpha\mu_0}{M_s V}\mathbf{m_f} \times (\mathbf{m_f} \times (\mathbf{H_{eff}} + \mathbf{h_{sto}} + \mathbf{H_{STT}}))$$

with α the Gilbert's damping ratio, γ the gyromagnetic ratio, μ_0 the magnetic permeability of the vacuum, M_s the saturated magnetization of the free layer and V its volume. $\mathbf{H_{eff}}$ is a field-like term including the different anisotropy terms and a possibly applied exterior field. At each time step, we draw each component of $\mathbf{h_{sto}}$ according to a Gaussian law determined by thermodynamical considerations [2].

FIRST RESULTS AND DISCUSSION

From multiple simulations at different values of the injected current density J_s, we obtained $< \Delta t >$ the average reversal delay of $\mathbf{m_f}$ presented on figure 2. With these results, we developped an analytical model that covers a wide range of J_s, based on existing analytical models in the extreme regimes [3] linked by a new mathematical expression of our own. Tests on a set of devices with different geometries and M_s provide good agrement with the results of simulation.

Furthermore, we studied the statistical distribution of the switching delay: the insets of figure 2 show some examples for different J_s values. We empirically developped a model of the delay distribution that uses a gamma law as probability distribution function (PDF). As we can see on the figure 2, its predicts correctly the general shape of the PDF extracted from the simulations results and tends to an exponential law in the weak current regime as the MTJ behavior becomes a POISSON's process (theoretical derivation in [2]).

Figure 3 shows that our compact model can also be fitted on experimental data measured in our lab and mentionned in [3], [4].

AN EXAMPLE OF HIGH-LEVEL USE

Thanks to a simulator using our compact model, we performed system-level simulations of an original car counting application. The chip architecture is neuro-inspired: the MTJs are used as binary stochastic "synapses" connecting input and output spiking neurons (figure 4). They learn in an unsupervized way, thanks to a "spike-timing-dependent plasticity" rule. These first results will be published at ISCAS 2014 [5].

CONCLUSION

From a physical equation, we have built up a compact model that describes the stochastic switching delay of a current-driven MTJ. Thanks to this model, we have explored through system-level simulations the relevance of MTJs as binary stochastic synapses in neuro-inspired chips.

ISBN 978-2-9547858-0-6

Acknowledgment

This work was supported by the ANR COGNI-SPIN project (ANR-13-JS03-0004-01) and the FP7 ICT BAMBI European project (FP7-ICT-2013-C).

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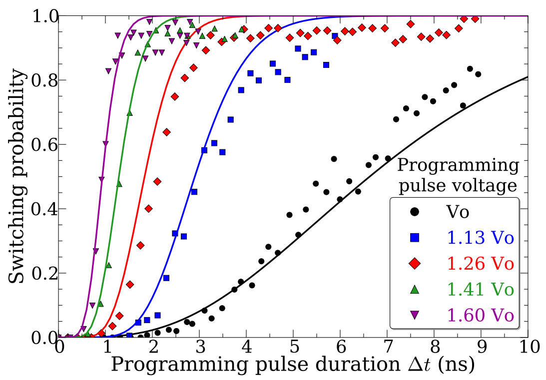
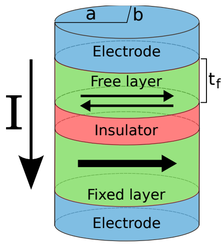


Fig. 3. *Symbols*: experimental measurement of the switching probability with respect to the duration of the applied programming pulse. *Solid lines*: fits using our compact model.

Fig. 1. A classical MTJ: a thin (< 1 nm) insulator between two ferromagnetic layers, often with an elliptical shape. The fixed one - has its magnetic moment (black arrow) pinned down along one direction whereas that of the free layer can take two stables directions, parallel (P) or antiparallel (AP) with the previous one. It leads to two different resistance states, R_P and R_{AP}. A positive current I can switch the device AP $\rightarrow$ P whereas a negative I can cause an P $\rightarrow$ AP event.



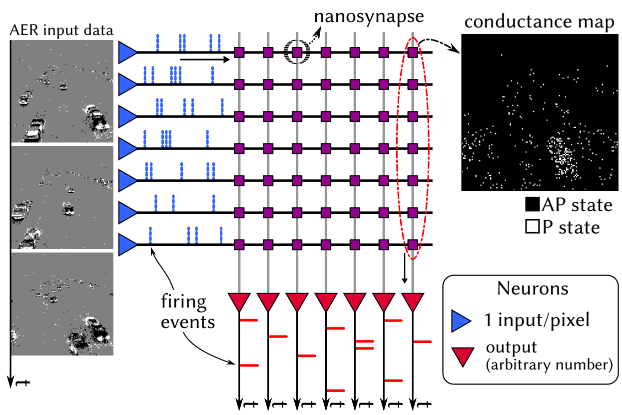


Fig. 4. Architecture of the simulated neuro-inspired chip: a crossbar of nanosynapses (purple ■) connects input spiking neurons (blue ▶) to output spiking neurons (red ▼). Each nanosynapse is made of a single MTJ. Initially, half of the synapses are in an R_P state. Thanks to a bio-inspired learning rule, the synapses' state evolves during the learning process. On the right side is given a post-learning conductance map that makes the associated output neuron fire only when a vehicle passes on a specific lane in the input "video" of cars on a 6-lanes freeway.

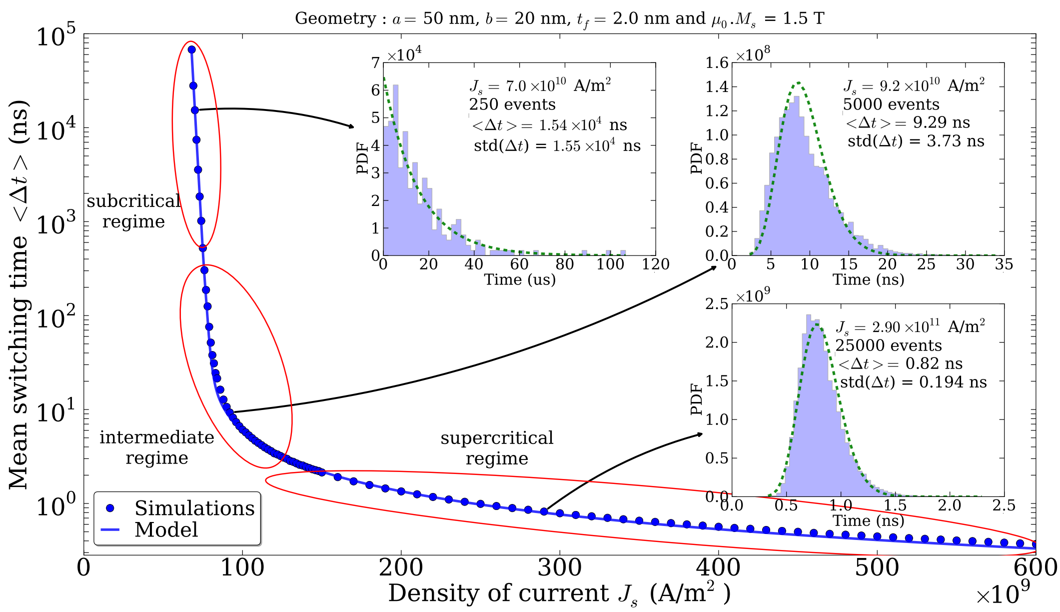


Fig. 2. *Main figure*: comparison between the results provided by our macrospin simulator and our model for $< \Delta t >$. *Insets*: probability distribution functions of Δt, for different values of J_s; simulations results (blue bars) *vs* our model (dashed green lines).