Compact Model of All-Optical Switching Magnetic Elements

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Abstract—We present, for the first time, a VerilogA compact model for an all-optically switchable Magnetic Tunnel Junction (MTJ) using results of All-Optical-Switching (AOS) simulations. Our model is compatible with electronics and photonics design automation tools, and was tested using *Cadence® Spectre®* and *Virtuoso®*. This compact model can be used to design circuits and systems combining MTJs, photonic circuits, and electronic circuits giving the possibility to researchers working within this field to develop novel circuits and systems.

Index Terms—Magnetic memories, Modeling, Circuit simulation, Magneto-optic memories.

I. INTRODUCTION

RECENT developments in bringing photonics, spintronics and electronics together to develop novel high-speed and low-energy memories [1] requires supporting simulation tools bringing different components from different technologies into a common platform. Therefore, as a first step, developing compact models enabling the design of circuits and systems using these new devices is essential. Such models require to link the photonic effect to the magnetic layer dynamics, and the magnetic layer dynamic to electrically relevant parameters such as the electrical resistance. MTJ models are available in literature and use magnetic equation (stochastic Landau-Lifshitz-Gilbert-Sloczewski, sLLGS) to derive the magnetization dynamic of the magnetic layer of the MTJ [2]–[6]. Such models are proper for characterising slow magneto-dynamic processes ($\approx ns$), but they fail to describe fast thermo-magnetodynamic behaviour of all-optical switching (AOS) in its full extent. AOS effect is a fairly recent discovery and is still the object of many research effort [1], [7]–[11]. AOS seems to be the result of a complex balance between the fast electron heating from an ultrashort light pulse absorption and the magnetic characteristics of a rare-earth transition metal compound (e.g. GdFe). Recent work on Landau-Lifshitz-Bloch (LLB) equation applied to a system of two interaction magnetic moment (e.g. Gd and Fe) shows a good agreement with atomistic modelling of temperature effect. However, these models struggle to reproduce the behavior above the Curie temperature, and have so far failed to represent pure optical switching of magnetization [12]–[20]. We present our work in section III on a stochastic LLB equation applied to a system

of two magnets and we show that this approach does not yet satisfactorily resolve the behaviour seen in pure AOS events. In this work, we integrate the two-temperature model that is commonly used to interpret ultra-short optical pulse interaction with matter [21], [22] in a VerilogA compact model. We connect this two-temperature compact model to another compact model we developed based on the results from atomistic simulation of thermo-magnetodynamic computed on the open access VAMPIRE code [23]. This allows us to resolve AOS event in a compact model that is compatible with circuit simulators. The combination of these two-compact model enables building an MTJ device with an all optically switchable free layer by combining our models with, for example, the model of [5]. We point out that our approach can be improved by developing and using a physical equation that represents AOS events in a computationally fast manner i.e. with a larger abstraction level than an atomistic model.

II. TWO-TEMPERATURE MODEL

Figure 1: Two-temperature compact model equivalent circuit. The capacitor value C is an integration constant used for the simulator computation only.

AOS is simulated based on results of a thermal model of the interactions between an ultra-short light pulses ($\leq ps$) and matter called the two-temperature (2T) model [21], [22]. This 2T model links the fast increase in temperature of the electron of the sample following its irradiation by an ultra-short light pulse and the thermodynamic between the electron and the

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lattice of the sample. This model can be described by the following system of differential equation:

$$\begin{aligned} C_{el} \frac{dT_{el}}{dt} &= -G_{el-la}(T_{el} - T_{la}) + P(t) \\ C_{la} \frac{dT_{la}}{dt} &= -G_{el-la}(T_{la} - T_{el}) + C_{la} \frac{(T_{la} - T_0)}{\tau} \\ P(t) &= \frac{|E(t)|}{\pi r^2 d} \alpha_{opt}, \quad C_{el} = \gamma T_{el} \end{aligned}$$

Where C_{el} , C_{la} , T_{el} and T_{la} are the electron and lattice heat capacity and temperature, G_{el-la} is the electron-lattice thermal coupling, τ is the lattice cooling time constant, T_0 is the surrounding temperature, $P(t)$ is the heat absorbed from the laser pulse, $E(t)$ is the input electrical field of the light pulse, d and r are respectively the thickness and the radius of the optical MTJ layer, and α_{opt} is the ratio of optical absorption through the optical MTJ layer.

We implement this code in VerilogA using an integrator circuit similar to the design described in [24]. The equivalent circuit of our model is presented in figure 1. It features two disconnected circuits, each with their own arbitrary heat sources, whose values are set by the term of the differential equation of the 2T model. They also have a capacitor with a value of 100 fF that is used to compute the time derivative of the electron and lattice temperature based on the heat sources of the two circuits.

A conservative thermal discipline that links the thermal potential to the heat flow was created for the model¹. We use the VerilogA CW laser model of MIT [25], [26] as an input optical field ($E(t)$) with a custom made Gaussian voltage source that drives the amplitude of the laser field leading to an optical Gaussian output pulse.

The circuit we use for testing our compact models is presented in figure 2. The circuit connects the laser source input with our AOS model using the two-temperature compact model we have developed. The parameters used for the simulations are presented in table I.

Figure 2: Circuit used in simulation. The MIT CW laser model is used with a custom-made Gaussian voltage source to simulate the electrical field of a Gaussian optical pulse.

Figure 3 presents an example of a Cadence® Spectre® simulation of our two-temperature VerilogA model. The results of the simulation in the upper graph show the envelope of the optical E field from the MIT CW laser model. Here, the carrier

¹All the parts of the model will be made open-access on the Nanohub platform at a later date.

Figure 3: Two-temperature compact model simulation with Spectre®. The upper graph shows the optical field input and the bottom graph the electron and lattice temperature response.

Figure 4: Two-temperature model comparison of Matlab numerical integration and Spectre® results.

frequency of the light is set to 0 for computational efficiency but the model allows multiplexing by the mean of an offset parameter (for more details, see [25]).

The electron and lattice temperature graphs plotted in the lower panel show, as expected, a fast increase of the electron temperature that quickly cools down to the lattice temperature.

P_{in} (W)	$FWHM$ (fs)	τ (ps)	γ_{el} (J/m ³ K ²)	C_{la} (J/m ³ K)	G_{el-la} (W/m ³ K)	r (nm)	d (nm)	C_{diff} (fF)	α_{opt} (°)
0.8	100	1	700	3×10^6	1.7×10^{18}	25	20	100	0.3

Table I: Two-temperature model parameters

The lattice cooling parameter was set to 1ps for clarity, it will, however, be set to 50ps for the AOS simulations. Figure 4 shows a comparison between a numerical integration of the 2T model coded in Matlab and the results from *Spectre*[®]. We see in the figure that the integration of the compact model matches the purely numerical integration in Matlab and we thus consider that our VerilogA two temperature model is valid.

III. NON-ATOMISTIC MODEL OF ALL-OPTICAL-SWITCHING

We have built a stochastic Landau-Lifshitz-Bloch (sLLB) simulation code based on the work of [12], [14], [16], [18], [20] in an effort to represent AOS switching events in a framework that is computationally fast. The sLLB model is used to describe the magnetization dynamics of a micromagnetic or macromagnetic system with temperature variation making this model a good candidate to represent thermal magnetic switching such as AOS. Our sLLB system is defined for two magnets A, B (i.e. Fe and Gd) following the work of [15], [16], the time-dependent magnetization of our A and B magnet is described by:

$$\begin{aligned} \frac{\partial \vec{m}_A}{\partial t} = & - \left(\vec{m}_A \times \vec{H}_{eff,A} \right) \\ & - \frac{\alpha_A^\perp}{m_A^2} \left(\vec{m}_A \times \left(\vec{m}_A \times \vec{H}_{eff,A} \right) \right) \\ & + \frac{\alpha_A^\parallel}{m_A^2} \vec{m}_A \left(\vec{m}_A \cdot \left(\vec{H}_{eff,A} + \vec{\xi}_A^\perp \right) \right) + \vec{\xi}_A^\parallel \end{aligned}$$

with $\alpha_A^{\parallel/\perp}$ the perpendicular and parallel damping parameters, and $\vec{m}$ is the A/B magnetization vector and $\vec{H}_{eff}$ is the A/B effective field more detail on these parameters and their definition can be found in [14], [16], [18]. $\vec{\xi}_A^{\perp/\parallel}$ are random vector used to represent the stochastic process and are defined from the solution of the Fokker-Planck equation as in [12], [16].

The temperature-dependent magnetic susceptibility is modelled in the same way as the work in [16] and is based on results from VAMPIRE simulations. We use an Euler-Heun scheme to numerically integrate our sLLB equation system for two interacting magnets Fe and Gd with the same parameters as the one used in the VAMPIRE simulation we computed to build our look-up tables (see Table III and Section IV). Despite literature results showing good agreement between a (s)LLB system simulation and an atomistic simulation of ultra-fast temperature behaviour [15], [16], [20], we could not produce results of a purely thermal AOS that corresponds to VAMPIRE results.

We compare in figure 5 typical simulation results with our sLLB system to VAMPIRE AOS simulation with a similar temperature input. We see in this figure that in the atomistic

Figure 5: Comparison of simulation results of an AOS event with a sLLB model and an atomistic model (VAMPIRE). The results are shown normalized for both atomic components (Fe and Gd).

approach, the magnetization is switched dynamically by the fast increase in electron temperature well above the Curie temperature (T_c) which is around 600K for this compound, whereas the sLLB magnetization response to a similar temperature pulse is clearly different. In the sLLB approach, the magnetization is quickly quenched by the temperature increase above T_c and the final magnetization switching is purely a result of the stochastic processes of the sLLB. Moreover, the sLLB temperature effect occurs much faster than the one seen in the VAMPIRE results, this could be why the sLLB fails to show AOS events. We make the hypotheses that in this form the sLLB above T_c magnetization's quenching occurs too fast and prevents the thermo-magnetic dynamic that results in AOS in the atomistic framework. We have performed a 100 simulations with the same sLLB system (same initial condition and same temperature input), we obtained a 48% rate of switching which is coherent with a purely random process but not with AOS events. As a comparison, we ran 100 VAMPIRE simulations on the same system with different random seed and got 97% switching for the same temperature input as the one in figure 5. Further study of AOS simulation with a sLLB system is beyond the scope of this paper. The rest of the paper will focus on a first approach compact model of pure AOS based on look-up tables instead of a sLLB-driven model.

x_{Gd} (0)	J_{Gd-Fe} (J/link)	J_{Gd-Gd} (J/link)	J_{Fe-Fe} (J/link)	$D_{Gd} = D_{Fe}$ (J/spin)	μ_{Gd} (μ_B)	μ_{Fe} (μ_B)	α (0)
0.25	$-1.09e^{-21}$	$1.26e^{-21}$	$2.835e^{-21}$	$8.07246e^{-24}$	7.63	1.92	0.02

Table III: Vampire simulation parameters from [8], the atomic structure simulated is an fcc cylinder with 50nm diameter and 20nm height.

H_k (T)	M_s (kA/m)	$N_x = N_y$ (0)	N_z (0)	dt (0)
0.953	800	0.30	0.39	0.01

Table IV: Spectre simulation parameters for a cylindrical magnetic element of same dimensions as the Vampire simulation.

Figure 7: AOS switching results for a 100 MHz optical pulse train. For these simulations, the height of the magnetic layer was increased to 100nm for stability; this changes the demagnetization coefficients as follow: $N_x = N_y = 0.460$, $N_z = 0.075$

be seen in the upper graph of figure 8. The lower graph shows the magnetization vector for both the VAMPIRE and the compact model simulations. We can see a slight temporal discrepancy between the two results. This can be explained by the difference in electron temperature input of the two models, as shown in figure 8, the Spectre and VAMPIRE temperature curves have about 2K difference during the electron temperature increase. Given that our model is based on the electron temperature input, it is not surprising that a small difference in electron temperature dynamic leads to a small difference in the magnetization dynamic: the compact model results have a delay of about 30fs. We consider that this delay is acceptable for the purpose of circuit simulation. The last step needed to make our AOS+LLGS compact model useful to electronic design automation (EDA) is to link it to an electrical signal. As such, substantial work on MTJ modelling can be found in literature e.g. [3]. We have designed our model so

Figure 8: Comparison of a VAMPIRE simulation of AOS and Spectre® LUT simulation, the compact model light input energy is set so that the 2T model matches the Vampire simulation up to a small error.

that it would be compatible with these MTJ models and thus allows a connection to electrical signals. In practice, we can use the magnetization vector output of our model as an input to the MTJ model free layer. The MTJ model computes a resistance value that depends on the angle between the free layer magnetization, which in our case is coming from our AOS magnetization model, and a pinned layer magnetization that can either be fixed to a specific value or be connected to a magnetization model to resolve its dynamic. This enables the design and simulation of optically written MTJ elements integrated with CMOS circuits in an EDA tool: e.g. optically controlled magnetic memories. Moreover, this also enables the exploration of effects such as noise in the light pulse amplitude or pulse broadening on the behaviour of AOS elements, which are of interest since AOS effects are strongly dependent on the light pulse absorbed energy (i.e. pulse amplitude) and on the timescale of this absorption (i.e. pulse width). Our model can also use spin-torque field input to resolve electrical effect on the optically switchable device. We note that our model does not resolve field effect during AOS events, to do so would require supplementary LUTs or a driving equation (see III). As such, our model does not resolve interaction between field effects arising from an applied magnetic field or a spin-torque and thermal AOS event.

V. CONCLUSION

We presented two VerilogA compact models that are combined to simulate time domain optical switching of a magnetic layer. These models can be connected to an MTJ transport model to obtain a simple optical magnetic tunnel junction that can be used in a circuit simulator such as *Cadence® Virtuoso®*. Our model is compatible with optical input in the form of the light's electric field's magnitude and phase, with spintronic input in the form of magnetic field and spin torque vectors, and output in the form of a magnetisation vector; this magnetisation vector can be used to simulate the conductance of an MTJ. The results of our model are validated against all-optical switching simulation that have been shown to reproduce all-optical switching experiments. The combination of our 2T and AOS+LLGS models enable design of circuit and system using all optical switching magnetic elements.

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