Compact SPICE Model of Topological Textures on Magnetic Racetracks for Design Space Exploration

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***Abstract*—Magnetic Topological Textures (MTTs) have the potential to become the building block of future memory and logic-in-memory devices due to their compact size and non-volatility. However, these MTTs are used in conjunction with the CMOS control circuit to design memory and logic-in-memory devices. Micromagnetic and SPICE simulations need to be carried out separately for MTT and CMOS, respectively, to evaluate the performance of these hybrid devices. Thus, a SPICE model that can emulate the physical behavior of the MTT would allow the designers to evaluate the performance of these hybrid devices accurately and enable design space exploration. In this paper, we build a compact and modular SPICE model of MTT nucleation, motion, detection, and annihilation on the racetrack by extracting parameters from micromagnetic simulation tools. We also build a CMOS-MTT generic racetrack circuit model in SPICE and validate the model's accuracy by comparing it with micromagnetic simulation results. As we can perform the simulations fully within SPICE while capturing the essential physics of the MTTs on the racetrack, we enable simulation runtime acceleration by a factor of $> 10^3$ and $> 10^6$ times approximately compared to the micromagnetic simulations carried out with OOMMF and MUMAX3. We envision that the proposed model will enable design and application explorations and device-circuit co-simulation, co-design, and co-optimization for the emerging MTT-based computing systems.**

***Index Terms*—Domain Walls, Micromagnetic Simulation, MUMAX3, Racetrack, Skyrmions, SPICE**

I. Introduction

Magnetic excitations such as skyrmions and domain walls are mobile, nano-sized, magnetic topological textures that are candidates for compact high-density memory [1] as well as possible bits in various unconventional computing schemes, such as temporal memory [2], temporal state machines [3] and reconfigurable non-volatile computing fabric [4], [5]. Micromagnetic simulation tools like OOMMF [6], and MUMAX3 [7] are widely used for microscopic simulation of these magnetic excitations, and recently a cycle-accurate architecture level racetrack memory simulator called RTSim [8] has been proposed. However, there is a lack of open-source compact SPICE models for intermediate circuit-level simulation to enable design space exploration.

As is often the case with magnetic switches, our analysis suggests that high impedance driving transistors tend to dominate the energy consumption in MTT-based circuits [2]. The hybrid nature (CMOS-MTT) of both conventional [9]–[11] and unconventional [2], [12] approaches suggest that there is a need for a simulation platform that enables designers to estimate energy consumption for the whole circuit, not just in the current-carrying heavy metal underlying the magnetic racetracks. Thus a compact SPICE model for MTTs that seamlessly captures the essential physics can accelerate the design space exploration of skyrmion/domain wall memory and logic devices. In this paper, we build a compact model for the nucleation, motion, detection, and annihilation of MTTs in the racetrack using the Modular Approach to Spintronics [13]. This approach captures the essential physics of MTTs in simulations performed entirely within SPICE while avoiding the computational burden of coupling a micromagnetics simulator with a circuit simulator. Further, we integrate all these modules in a generic racetrack structure along with the CMOS control circuitry and show that the SPICE model emulates the magnetic behavior successfully. Since we perform the entire simulations in SPICE, we are able to accelerate simulation runtime by a factor of $> 10^3$ and $> 10^6$ times approximately compared to the micromagnetic simulations with OOMMF [6], and MUMAX3 [7], respectively for a large unit cell.

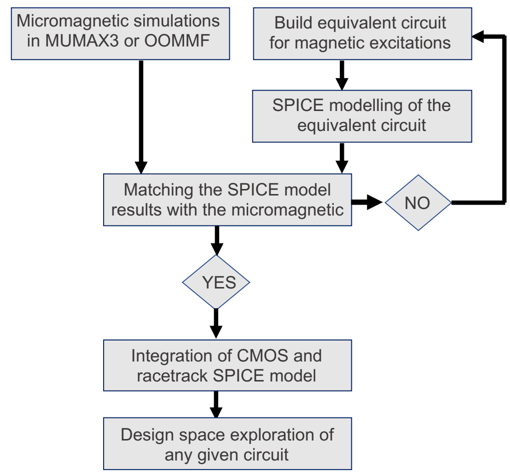

Fig. 1. Micromagnetic to SPICE flow for the compact SPICE model of magnetic topological textures on racetrcaks.

II. Methods: Physics to circuit

We develop a circuit module for skyrmion nucleation, motion, detection, and annihilation. However, by modifying the velocity equations, the proposed module can be adopted for domain walls and other magnetic excitations. We build an equivalent circuit for skyrmion nucleation, motion, detection, and annihilation. We then model the SPICE subcircuit and integrate the SPICE subcircuit with other circuit elements. Finally, we verify the correctness of the proposed circuit module by comparing the results with micromagnetic simulations done with the same parameters. Figure 1 shows the proposed micromagnetic to SPICE only model design and verification flow.

A. Magnetic Topological Texture Physics

Dynamics: To model the motion of skyrmion/Domain walls, we use a collective coordinate description of a rigid skyrmion, that is, we assume the skyrmion texture has only translational degrees of freedom and derive equations for these from the governing Landau-Lifshitz-Gilbert equations. We assume that the only driving forces on the skyrmions come from spin orbit torques arising from the spin Hall effect (spin Hall angle Θ_{sh}) in the heavy metal layer. The resulting Thiele equation gives an instantaneous speed for the skyrmion [14], [15]

$$v = \frac{\pi\gamma\hbar}{2e}\frac{I_d\Delta}{\sqrt{(4\pi)^2\langle N\rangle^2+\alpha^2\mathcal{D}_{xx}^2}}\frac{\Theta_{\text{sh}}}{\Sigma_i t_i M_{s_i}}j, \tag{1}$$

Writing for each component:

$$v_x = \frac{4\pi B\theta_{SH}(\cos\psi' j_x + \sin\psi' j_y)}{\sqrt{\alpha^2 S(T)^2\mathcal{D}_{xx}^2+(4\pi S_N(T))^2}} \tag{2}$$

$$v_y = \frac{4\pi B\theta_{SH}(-\sin\psi' j_x + \cos\psi' j_y)}{\sqrt{\alpha^2 S(T)^2\mathcal{D}_{xx}^2+(4\pi S_N(T))^2}} \tag{3}$$

where $\psi - \theta_0 \equiv \psi'$, $B = \pi\hbar I/2q$, $S(T) = \Sigma_i M_{s_i}(T)t_{F_i}/\gamma_i$ is the spin angular momentum summed over volume, $S_N(T) = \Sigma_i N_{sk_i} M_{s_i}(T)t_{F_i}/\gamma_i$ is the topological spin angular momentum and $\tan\theta_0 = 4\pi\langle N_{sk}\rangle/\alpha\mathcal{D}_{xx}$ with $\langle N_{sk}\rangle = S_N/S$. Where j is the electrical current density in the heavy metal layer, t_i is the thickness of that layer, Δ is the characteristic domain wall length, M_s is the saturation magnetization in each layer of the synthetic antiferromagnet, α is the Gilbert damping, and γ is the gyromagnetic ratio. The property of the skyrmion texture is the (integer) winding number $N_{sk_i} = (4\pi)^{-1}\int \mathbf{m}_i\cdot(\partial_x\mathbf{m}_i\times\partial_y\mathbf{m}_i)\,\mathrm{d}x\,\mathrm{d}y$.

Nucleation: There are various methods of nucleating skyrmions; the most popular one which is compatible with digital circuits is by applying current pulses. The current pulse can be through a nano-contact or through the heavy metal layer. For the former method, it can be simulated in SPICE by adding a resistor and use the data on current pulse amplitude and time from micromagnetic simulations (or experimental results). For the latter, we do not need to add any extra resistor to the circuit and use the current amplitude and time; the important property, in this case, is the existence of impurities in the heavy metal layer, which does not affect the circuit operation.

Annihilation: For skyrmion annihilation, a high driving current can be used to annihilate skyrmions either at the boundaries or designated non-idealities in the racetrack. The minimum required current and time can be determined from either simulations or experiments. These numbers for current and time then will be inputs of the circuit.

Detection: To electrically detect skyrmions, there are two popular methods. One would be to use an MTJ stack. An MTJ stack has different resistances for parallel and anti-parallel states. In this case, skyrmion acts as the free layer of the MTJ stack with a reduced TMR effect. The way to simulate MTJ in a circuit is by considering it as a variable resistance. Another method for detection of skyrmions is by using anomalous hall effect (AHE). Due to AHE, a voltage difference along the perpendicular direction to the driving current exist. This voltage difference is a function of the position of the skyrmion, which can be used for detection. In this case, there would be no need for an extra resistance compared to the MTJ method for circuit simulations, only the voltage swing from AHE will be an input for the circuit simulation.

B. Modular Approach of Modeling MTTs in the Racetrack

The bottom-up modular approach for building the MTT model allows for the most generalized method of modeling such multi-physics systems since it allows us to incrementally build more complex designs of device structures much like a lego block model is assembled. As an example, we can emulate the effect of multiple MTJ readouts to the same racetrack by attaching additional MTT detection modules to the MTT motion modules, with only the appropriate geometrical information provided as a design parameter. This is made possible due to the exposure of all state variables of the underlying physical system, such as the position of the MTT on the racetrack, the magnetization direction of MTJ, etc. Our approach has a distinct advantage over alternate modeling approaches that build a monolithic model without explicit state variables, thereby rendering them either non-reusable or non-expandable for other device configurations and designs. Our approach is in line with conventional wisdom vis-a-vis the modularity and re-usability of libraries in building large and largely error-free software systems.

In our circuit model, we implement the MTT nucleation module by using a comparator which is implemented as a Voltage Controlled Current Switch (VCCS) and triggers on if the spin-polarized current from the write MTJ is larger than the minimum required current for MTT nucleation (see Figure 2(b)). This charges up a capacitor that stores the existence of the MTT as a state variable. The state variable, in turn, drives a multiplier implemented as a Voltage Controlled Voltage Switch (VCVS) that also considers the MTT annihilation. The procedure develops the MTT existence state at a location, which is then provided to the MTT motion module. Next, the MTT motion module implements the Thiele equation [16] as a Current Controlled Current Switch (CCCS) and a capacitor. The CCCS outputs the MTT velocity driven by the input spin-current from the heavy metal, and the charge is then integrated over the simulation time across the capacitor. The voltage on the capacitor represents the MTT location along the racetrack (a state variable). After that, the MTT detection module consists of a VCVS comparator that compares the

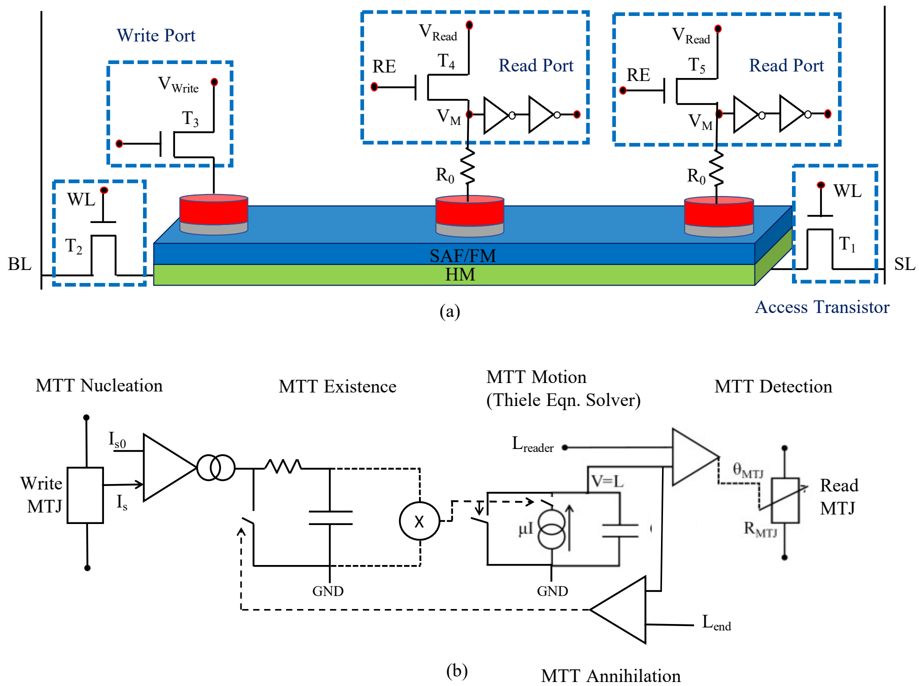

Fig. 2. (a) Generic MTT racetrcak memory circuit capable of nucleating, moving, detecting and annihilating skyrmion. (b) Equivalent circuit for MTT nucleation, motion, electrical detection and annihilation.

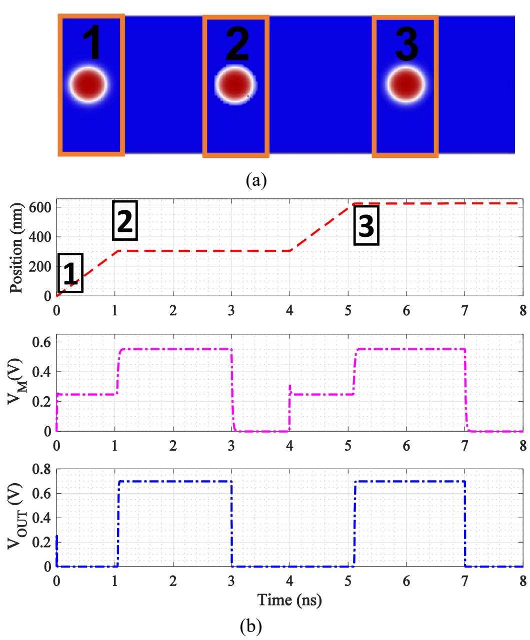

Fig. 3. (a) Micromagnetic simulation of skyrmion motion in a magnetic racetrack done in MUMAX3. Here positions and times are: $1 : x = 42\ nm, t = 0\ ns, 2 : x = 300\ nm, t = 1.2\ ns3 : x = 600\ nm, t = 2.4\ ns$ and (b) SPICE simulation of the circuit presented in Figure 2(a) with the same simulation parameters as micromagnetic simulation. The change in voltage at node M, V_M, when a skyrmion reaches under a read port clearly depicts that our SPICE model successfully captures the MTJ resistance change.

MTT position to the MTJ position, which then determines the reader MTJ's resistance by changing the free layer magnetization. This can be read through the TMR effect using a voltage divider circuit [2]. Finally, the MTT annihilation module compares the instantaneous MTT position with the racetrack end position as a VCVS. Once the MTT reaches the end of the track, it turns on, which then resets the MTT existence state variable by draining the charge on the capacitor in the MTT existence module. This then further stops the MTT motion module and discharges the capacitor, thereby resetting the MTT coordinates.

This modular approach implements a complete end-to-end MTT nucleation-motion-detection-annihilation cycle self-consistently within SPICE while capturing accurate timing of these events (see Figure 3), which depend on the fulfillment of required conditions, such as sufficient spin current for a sufficient time duration for MTT nucleation, detection of the MTT under the MTJ, and annihilation when it reaches the end of the track. This approach is also expandable; as an example, multiple MTT readers can be implemented simply by attaching multiple MTT detection modules to the MTT motion module. 2D motion and edge annihilation can similarly be implemented by an additional MTT motion module that captures the motion along the width direction and an additional MTT annihilation module for the appropriate width dimensions. Multiple MTTs can be implemented using multiple combinations of these modules, while mutual MTT repulsion on the same racetrack can be implemented by a coupling module that compares the position of two different MTT motion modules and modifies the velocity of the MTTs accordingly.

TABLE I
SIMULATION RUNTIME COMPARISON.

	OOMMF	MUMAX3	SPICE
Runtime 64,000 cells	$<$ 7,200s	384s	$<$ 1s
Runtime 2,560,000 cells	$>$ 360,000s	$>$7200s	$<$ 1s
GPU Requirement	No	Yes	No

III. RESULTS AND DISCUSSION

We perform both micromagnetic, and SPICE simulations with Intel Xeon Gold 6148 single-core CPU and 980 TI, GPU model, and the comparison of simulation runtime is shown in Table I. The memory and time requirement of the micromagnetic simulations are strongly dependent on the number of cells and simulation time used, which is not the case for the proposed compact SPICE model. For larger unit cell numbers $> 10^6$ and simulation time of above 10 ns, MUMAX3 takes hours to simulate even with the use of a GPU, and zero temperature simulation [17] while the non-zero temperature simulations typically involve millions of Monte Carlo runs that can extend the runtime to more than a day.

Apart from the simulation runtime acceleration, our proposed compact SPICE model enables the user to estimate both component-wise and whole circuit energy consumption accurately. The designer can also perform device-to-circuit variation and performance analysis of their design and choose optimized parameters to ensure the best performance of their design. These analyses are vital to building large-scale custom chips.

In the future, we plan to extend the Thiele equation [16] for skyrmions (one of the MTTs) to include external forces acting on it as well. The external forces can be approximated and fitted to the micromagnetic simulations. By adding the effects of the external force to the Thiele equation, we can modify the mobility term of skyrmion (or any MTTs). This can be used to include effects from temperature or defects to make the SPICE results more accurate [1].

IV. CONCLUSION

A SPICE simulation model that can accurately emulate the physical behavior of MTT on the racetrack will ease the adoption of MTT-based computing systems as the SPICE simulation is fast and enables design space exploration. Moreover, component-wise energy consumption, as well as the energy consumption of large-scale custom CMOS-MTT chips, can be calculated from SPICE simulation. Thus, our proposed compact SPICE model of MTTs on a racetrack fills the gap of a circuit-level simulation platform. We adopt the bottom-up modular approach of spintronics to build the proposed model that can accurately capture the essential physics of MTTs in SPICE. We believe this is an important step towards the emergence of this promising technology to the cusp of the actual product. Furthermore, using the same micromagnetic to SPICE flow, the compact SPICE model can be extended to include thermal fluctuations and non-idealities such as point and grain defects. This would allow us to realistically evaluate and compare MTT-based device performance with existing CMOS and emerging devices.

ACKNOWLEDGEMENTS

This work is funded in part by the Defense Advanced Research Projects Agency (DARPA) Topological Excitations in Electronics (TEE) program (grant D18AP00009).

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