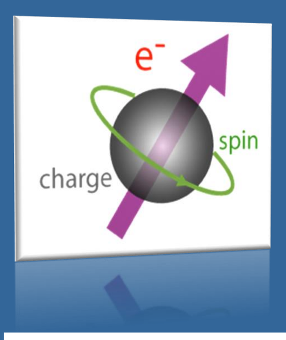
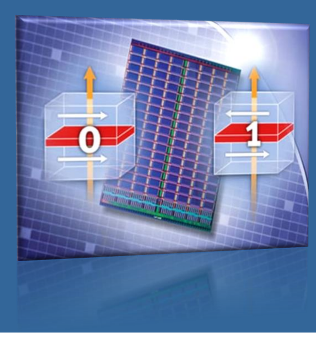
Modeling and Simulation of All-Spin Logic Device





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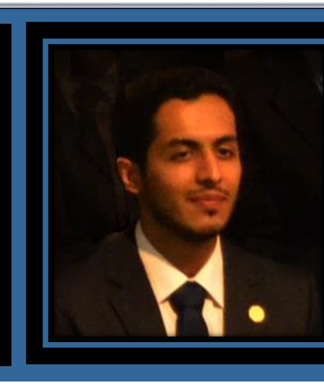



INTRODUCTION

With the various challenges facing CMOS technology such as increased power density and degraded energy efficiency, people are looking for alternative technologies to sustain the advancements of Moore's law (Figure 1). Spintronics one possible route, and is an emerging field in which information is stored in the alignment of spins rather than (or in addition to) the charge.

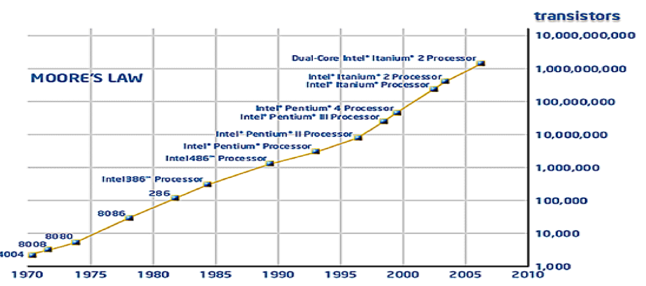


Figure 1. Moore's law.

Among the recent spintronic devices proposals is a device called all-spin logic (ASL) that has recently shown increased interest due its low power operation and usage of pure spin currents. As shown in Figure 2, a simple ASL device consists of two nanomagnets that can be switched using pure spin currents through spin-transfer torque (STT). Using ASL, two fundamental logic operations can be achieved: (1) Invert, and (2) copy. For example, applying a positive voltage in terminal 1 will accumulate spins underneath the input nanomagnet, which will result in a spin diffusion current that can switch the output nanomagnet antiparallel to that of the input.

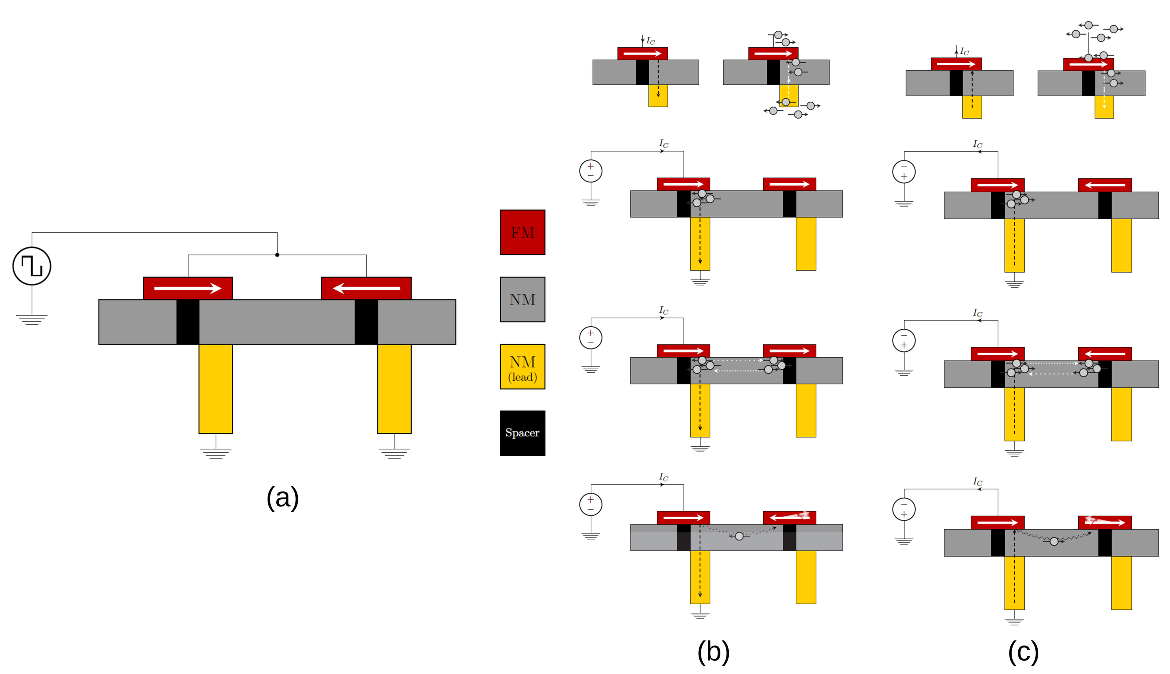


Figure 2. (a) Basic ASL switch. Illustration of (b) invert and (c) copy. Figures adapted from [1].

OBJECTIVE

The main goal of this project is to design circuit modules that can be used as basic simulation blocks for spintronic devices in general, and ASL in particular. The programming language we used was Verilog-A since it is ideally suited for compact modeling. To verify the accuracy of the modules, we simulated basic ASL circuits and reproduced previously published results.

METHODOLOGY

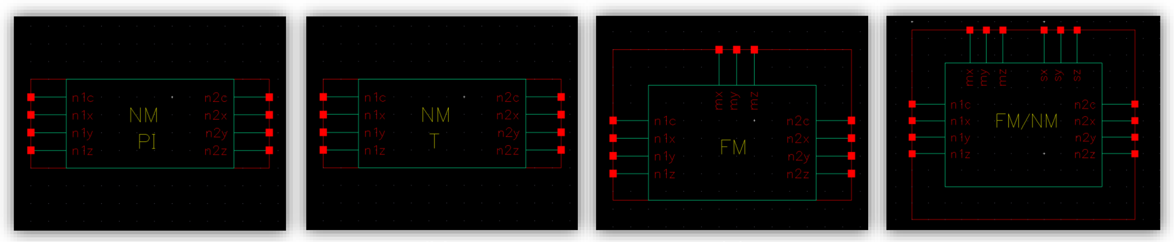
Given a ferromagnetic (FM)/nonmagnetic (NM) multilayer, we can classify the modules needed into the following:

I. Bulk FM material.
II. Bulk NM material.
III. FM/NM interface.
IV. Landau-Lifshitz-Gilbert-Slonczewski (LLGS) solver.

The generalized circuit theory (also known as spin circuit theory) relates the total charge and spin currents with a conduction a matrix as follows

$$\begin{bmatrix} I_C \\ I_{S,x} \\ I_{S,y} \\ I_{S,z} \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} \\ G_{21} & G_{22} & G_{23} & G_{24} \\ G_{31} & G_{32} & G_{33} & G_{34} \\ G_{41} & G_{42} & G_{43} & G_{44} \end{bmatrix} \begin{bmatrix} V_C \\ V_{S,x} \\ V_{S,y} \\ V_{S,z} \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (1)$$

The first three modules are thus modeled by special 4×4 conduction matrices derived from drift-diffusion equations [3]. The modules are shown in the figure below.



(a) (b) (c) (d)

Figure 3. Schematic design for (a) NMPI (b) NMT (c) FM (d) FM/NM.

The fourth module is a block to simulate the LLGS equation

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{eff} + \gamma\alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} + \boldsymbol{\tau}_{STT} \quad \ldots\ldots\ldots\ldots \ (2)$$

The block solves a system of ordinary differential equations. In circuit terminology, differential equations are modeled by a capacitor and dependent current source [2] as shown in Figure 4.

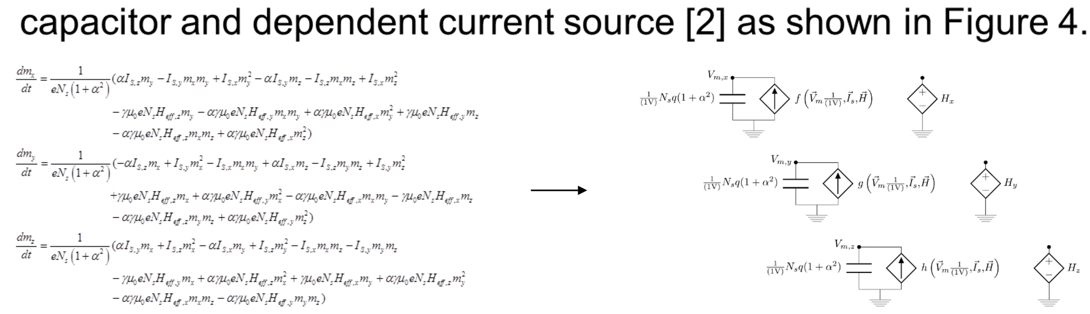


Figure 4. LLGS solver model [2].

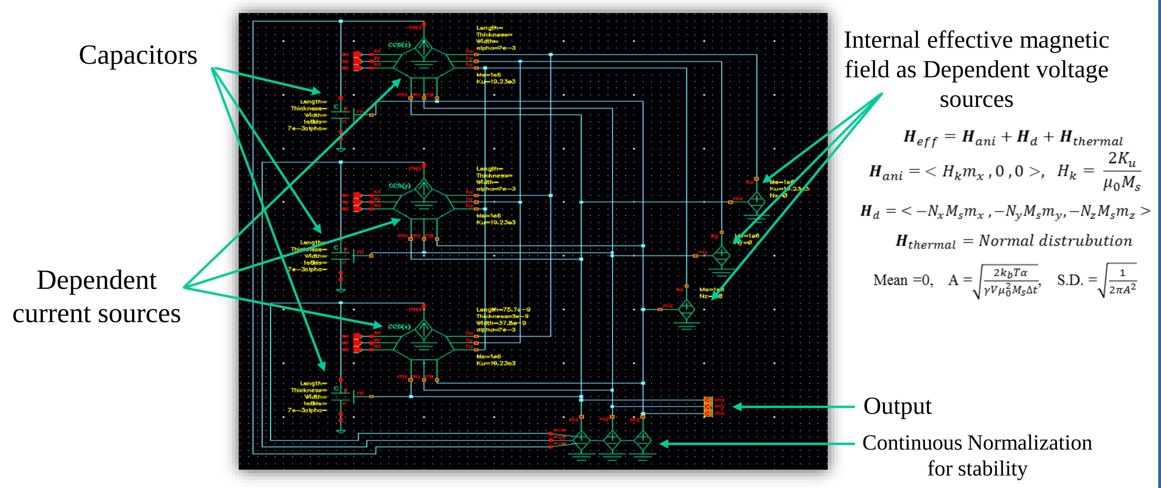


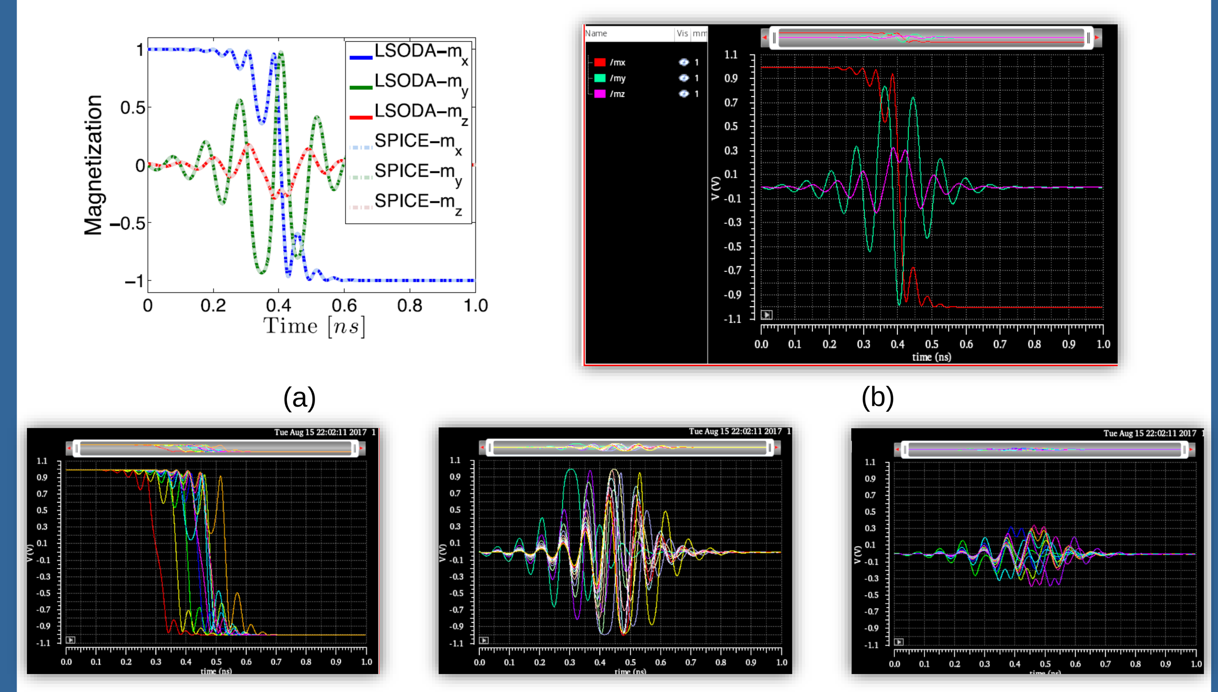
Figure 5. LLGS solver schematic design.

RESULTS

The compact modules were verified by a comparison with previously published results.

LLGS solver validation

Below we show the results of switching the magnetization from $\mathbf{m} = (1,0,0)$ to $\mathbf{m} = (-1,0,0)$ by providing a spin current of $\mathbf{I}_S = (3,0,0)$ mA. The results are shown in Figure 6.

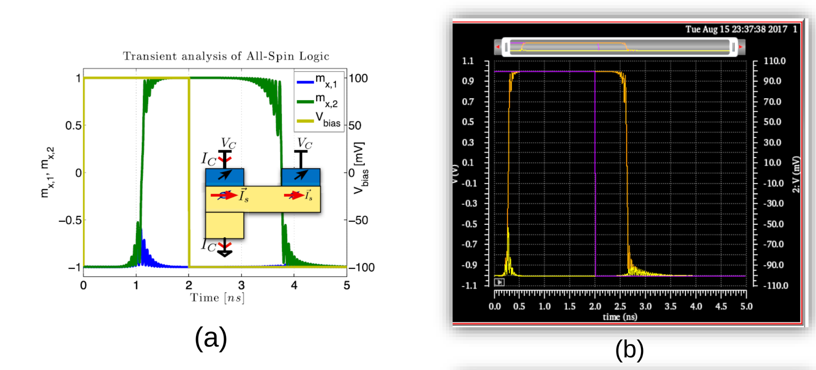


(a) (b) (c) (d) (e)

Figure 6. LLG solver validation by (a) LSODA, SPICE [2] and (b) Verilog-A. After using different initial conditions of m_x=100:100:1000, m_y=1 and m_z=1 we got (c) m_x, (d) m_y and (e) m_z .

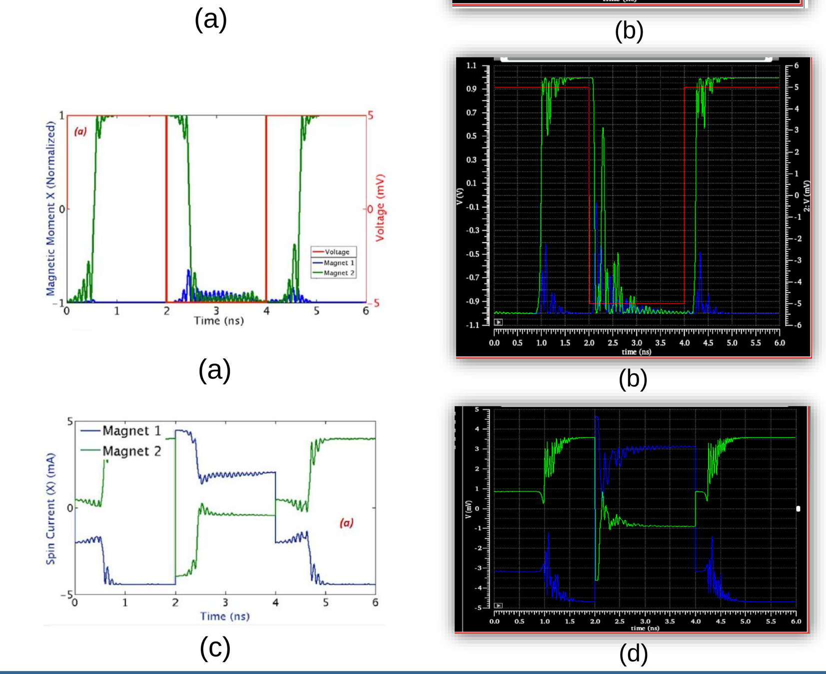
Simulating ASL device

After approximating some parameters, we were able to reproduce several simulation results of ASL using our Verilog-A modules. In Figures 7-9, we show the invert and copy operations of an ASL device plotted versus the simulation results shown in [1]-[3].



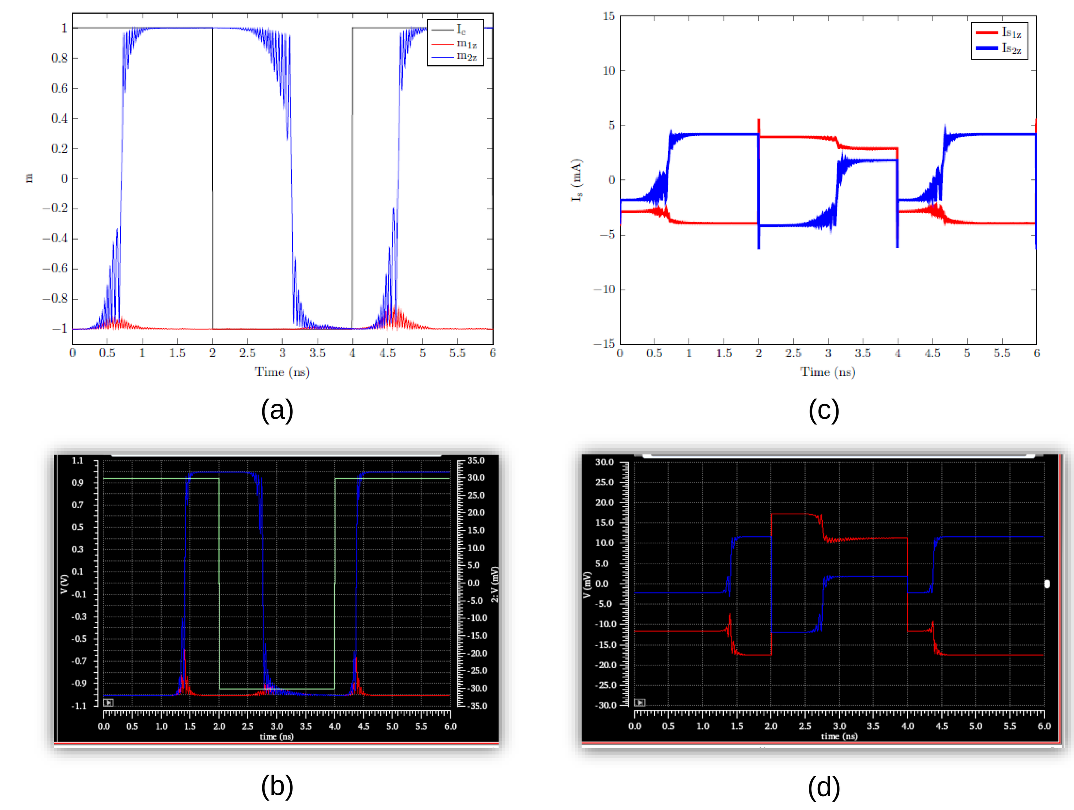
(a) (b)

Figure 7. ASL device with an input square pulse supply voltage of magnitude 100mV and period 6ns. (b) is the reproduced result of the magnetization direction from (a) [2].



(a) (b) (c) (d)

Figure 8. ASL device with an input square pulse supply voltage of magnitude 5mV and period 4ns. (b) is the reproduced result of the magnetization direction from (a) [3]. (d) shows the spin current which resemble the behavior of (c) from [3].



(a) (c) (b) (d)

Figure 9. ASL device with an input square pulse supply voltage of magnitude 30mV and period 4ns. (b) is the reproduced result of the magnetization direction from (a) [1]. (d) shows the spin current which resemble the behavior of (c) from [1].

CONCLUSION

- The most basic building blocks of spin circuits for single domain magnets were created in Verilog-A .
- Realistic results of the LLGS solver module were shown.
- Switching time delay of magnetization have some dependence on the thermally perturbed initial angle.
- ASL device was simulated based on parameters from three different sources.
- We obtained good similarity in the overall behavior from the reproduced results.

REFERENCES

[1] M. Alawein. Circuit simulation of all-spin logic, 2016.

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[3] S. Manipatruni, D. E. Nikonov, and I. A. Young, "Modeling and design of spintronic integrated circuits," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 59, no. 12, pp. 2801–2814, Nov. 2012.