

Spin Switch: Model built using Verilog-A Spintronics Library

Samiran Ganguly, Kerem Y. Camsari, Supriyo Datta
Purdue University

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Abstract

We present a circuit/compact model for the Spin Switch created using a Verilog-A based library of “spintronic lego blocks” building upon previous works on spin transport. This modular approach allows considerable ease in integrating diverse physical theories needed to build models for complex spintronic devices. This approach further allows flexibility of inclusion of new materials and phenomena in existing spin device designs, critical in keeping pace with developments in the field of spintronics.

The Spin Switch [1] is a complex spintronic device, based on a combination of multiple spin transport effects viz. Giant Spin Hall Effect (GSHE), Spin-Transfer Torque (STT), Tunneling-Magneto Resistance (TMR) along with nano-magnet dynamics (LLG eqn.) and dipolar coupling of thin film magnets, and demonstrates device properties of gain, I/O isolation, and non-volatility. In addition, these switches connect to each other using ordinary charge currents, making it a potential candidate for novel applications in large scale circuits.

1 Introduction

Last decade and half has seen rapid development of spintronics emerge as potential technology for “beyond-CMOS” circuits. This has primarily been possible due to new discoveries that has caused convergence of spin transport through nanostructures and behavior of thin film magnets, described by very different theoretical methods in a single device. Every few years, new materials and phenomena, such as Giant Spin Hall Effect, Topological Insulators etc. are discovered. It is challenging to incorporate new materials and diverse physical phenomena in a single device model.

To address this challenge we have created a library of basic modules [2][5] created in Verilog-A that can be connected together to build circuit models of spintronic devices that can be simulated and analyzed using circuit simulation software, such as SPICE. This modular approach to building models for complex spin devices allows to rapidly create and evaluate new device designs and incorporate new materials and phenomena as they are discovered in future.

The Spin Switch is an example of a spin device that shows device characteristics such as gain, I/O isolation and non-volatility[1]. In the next few sections we discuss the library modules briefly, discuss how the spin switch model can be built using the modules and a few demonstration simulation using the spin switch model.

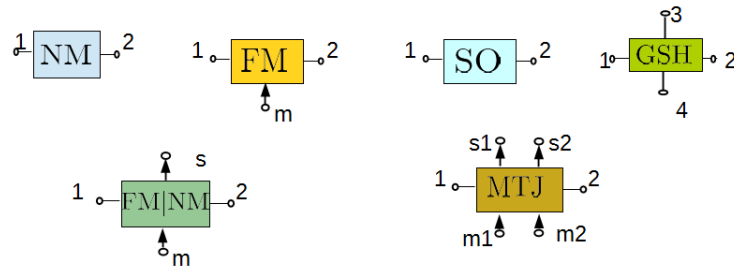
2 Library of Modules

The library 1 contains a collection of modules dealing with spin transport through different kind of materials or behavior of nano-magnets. The library at present contains modules for:

- **Non-Magnet (NM):** Any material without any special magnetic properties, e.g. Cu, Si etc. This module can be modeled using “spin diffusion theory”.

- **Ferromagnet (FM):** A magnetic material e.g. CoFe, NiMn (also called Permalloy) etc. This module is modeled using spin diffusion theory.
- **Interface between NM and FM (NM-FM):** A block for material interface. This is a separate module in contrast with the previous two blocks because the interface has transport properties (Spin-Transfer Torque) that cannot be captured using spin diffusion theories, rather it requires quantum mechanical treatment to accurately capture the transport properties.
- **Spin Orbit (SO):** A semiconductor showing Spin Orbit coupling effect, e.g. GaAs. This module is developed using quantum transport (NEGF) theory.
- **Giant Spin Hall Effect (GSHE):** A metallic material showing the Giant Spin Hall Effect, e.g. Pt, Ta, W etc. This is modeled using spin diffusion equation.
- **Magnetic Tunnel Junction (MTJ):** A composite device made of two magnets separated by a thin tunneling oxide layer. This device requires a model of its own because it cannot be broken down into simpler pieces using conventional circuit theories. The module requires quantum transport theory (NEGF) for accurate modeling.
- **Magnet-Dynamics Solver (LLG):** This module captures the dynamics of the magnetization of thin film magnets. This module, in contrast with the above modules, captures phenomena/behavior rather than a physical structure in itself. The module solves the Landau-Lifshitz-Gilbert Eqn in a single-domain approximation, which is reasonably valid for magnet dimensions of the size encountered in typical spintronic applications.
- **Magnetic Coupling (Coup):** A module used to capture the magnetic field/coupling between two magnets/domains, e.g. in Spin Switch model it is used to model dipolar coupling between an FM and an MTJ.

Spin Transport:



Magnetics:

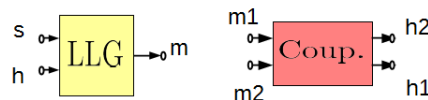


Figure 1: Library of Spintronic Modules

The modules are developed using the 4-component spin circuit theory, where physical quantities at each “terminal” of a device are not ordinary (scalar) voltages and currents, rather 4-component vectors, 1 for charge and 3 for spin. Explicitly having the spin quantities at the terminals allows the modules to interact

with each other using spins. Without this interaction, it will not be possible to build complex spin devices using smaller reusable modules. The details of the modules shall be covered in publications some of which are referenced at end of this document. This guide merely lists the modules, their ports/terminals, parameters and demonstrates their usage using the Spin Switch device.

Table for Modules

Module	Parameters	Ports	Name
NM	A, L, rho , lsf	1, 2	lsnonmagnet
FM	A, L, p , rho, lsf, lsft	1, 2, m	lsferromagnet
FM-NM	gint , p, sl, fl	1, 2, m, s	lsfmminterface
SO	g0 , L, eta, ms	1, 2	lssoc
GSHE	A, L, t, rho, lsf	1, 2, 3, 4	lsgsh
LLG	Ms, A, t, alpha, Hk, Kx, Ky, Kz	m, s, h	lsmonodomainllg
Coup	K12xx, K12yy, K12zz, K21xx, K21yy, K21zz	m1, m2, h1, h2	lscoupling

Where:

A = area, L = length, t = thickness, p = polarization, g0/gint = conductance, K = coupling coefficients, alpha = damping coefficient, Hk = anisotropy field magnitude, Ms = saturation magnetization.

Numbered ports are physical ports, which connect to other materials and are 4-component types. The named/letter nodes denote special connections dealing with magnetics part of the circuit. E.g. the m denotes the magnetization vector, it is “output” from and LLG and goes in as input to the FM, so that the LLG block can provide the magnetization information to the FM. Similarly the s terminal is used to pass the spin current information to the LLG block. The h terminal is to pass magnetic field to the blocks. The m, s and h are all 3-component blocks, whose voltage denote the magnitude of the quantity the represent.

3 Spin Switch Device

The Spin Switch 2 was proposed in 2012 [1] as a device showing I/O isolation and gain, and non-volatility. Furthermore, the Spin Switch connects to any external circuit using charge currents only, which makes it a potential candidate for large scale circuit design. We briefly describe the spin switch below.

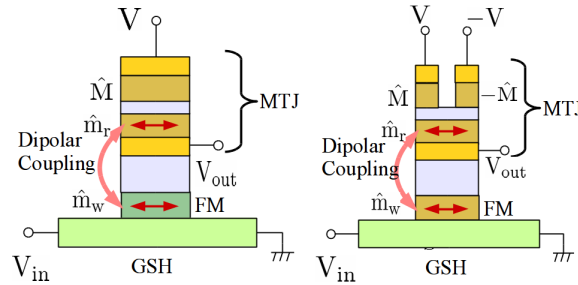


Figure 2: Spin Switch devices: (left) Single MTJ version and (right) “Dual” MTJ version. The single MTJ version has the normal MTJ as the reader, but the dual MTJ version has two opposing fixed layers with a shared common free layer.

The spin switch is composed of two units:

Write A GSHE material injects spin current in the FM layer. If enough spin current has been injected, it can flip the magnet or “Write” information into it.

Read An MTJ sits on top of the FM separated by an insulator layer. However, due to dipolar coupling, the MTJ can read off the state of the FM layer, i.e. as the FM switches, it switches the free layer of the

MTJ and the resistance of the MTJ changes. This difference in the resistance between the two states is the basis of the read operation

Since the two units are electrically isolated, they can be biased individually without interfering with each other. This is useful in providing a large fan out without loading down the input stage much. The gain is obtained due to the fact that the input charge current can produce a spin current larger in magnitude than itself, which allows a smaller swing in input stage to provide a large swing in output stage, showing a “transistor” like behavior that can be useful in certain applications. Non-volatility is inbuilt in the device as the information as the state of the device is stored in a magnet which does not require any external power supply to store any information.

4 Modeling and Simulation of the Spin Switch

The Spin Switch can be modeled as a circuit built using the modules described before. For both the designs, on the left side of the circuit are the two LLG blocks connected using the dipolar module. This is the magnetic connection between the input and output stages. On the bottom is the WRITE stage which consists of the GSHE driving the FM and the top is the READ stage. The Only difference in the two designs is the MTJ of the READ stage. In the single MTJ design, it is a normal MTJ and the swing of the output voltage is unipolar, however in the dual MTJ design consists of two MTJs sharing a common free layer and this causes a bipolar swing of output voltage.

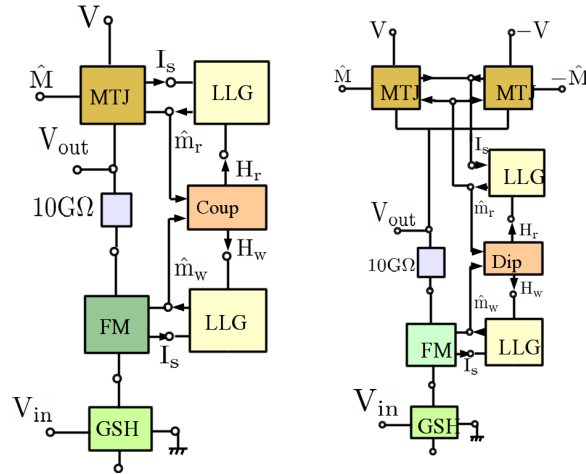


Figure 3: Spin Switch device designs modeled as a circuit built of spintronic modules (left) Single MTJ Spin Switch (right) Dual MTJ Spin Switch

The file `ssmodel.sp` lays out the two circuit-model netlists built using the library modules and the test-benches, `ssstestbench.sp` and `ss2MTJtestbench.sp` creates transient simulation setups.

Fig 4 shows one single transient switching transient of the devices. We trace the z-component of the FM and the MTJ layer as the device switches and it can be clearly seen that the two magnets are in opposition, as expected from dipolar coupling. As a result the output of the MTJ swings as well. The single MTJ device’s output swing is between two positive values, however the dual MTJ device’s output swing is bipolar and shows that its a better design for CMOS like operation. It can also be seen that the switching time of these devices is less than a nanosecond.

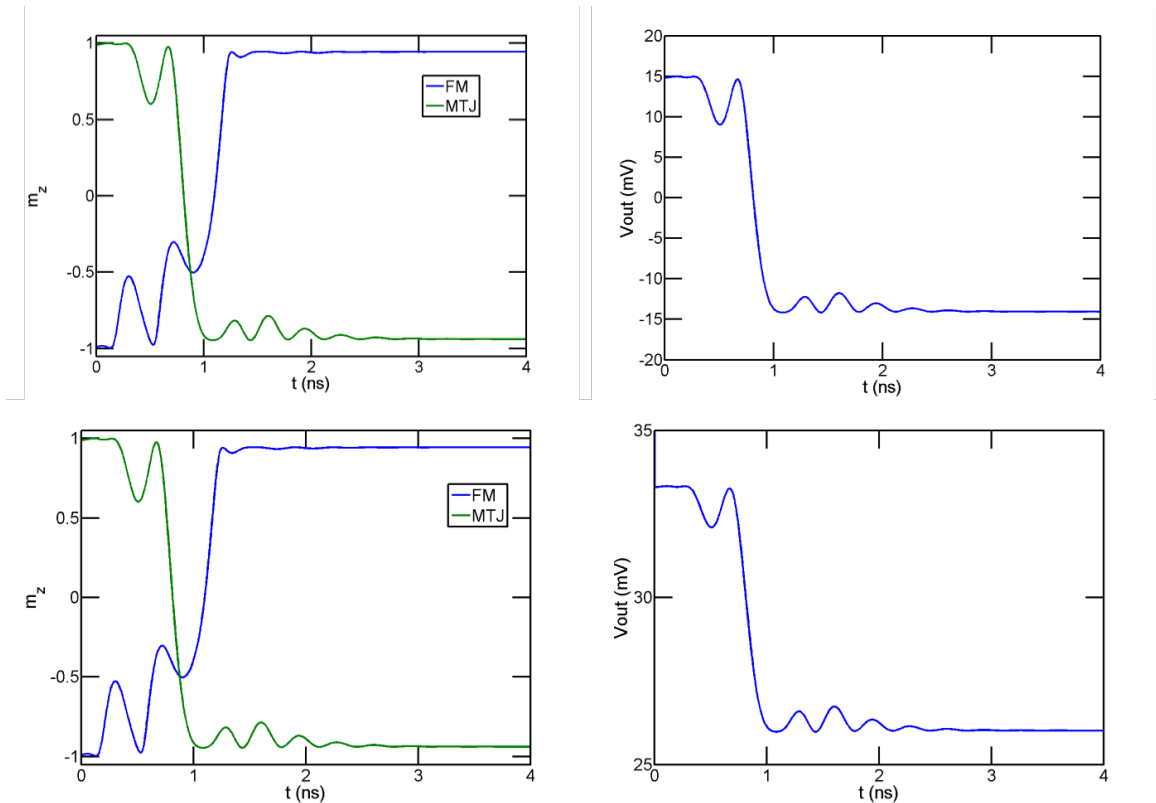


Figure 4: Transient simulation of a switching event for the two designs (top) Dual MTJ Spin Switch (bottom) Single MTJ Spin Switch

5 Some thoughts on Simulation

The device netlist and simulation testbenches were created for HSPICE platform. For a different platform compatibility edits might be necessary. However the netlists use only the libspin modules and hence should be useable with any other simulator as well.

It is critical to initialize the magnets with a proper “direction” as is done in the testbench. Without this step, the internal magnetic field for the LLG cannot be setup, which will result in either simulation failing or giving garbage results.

The time step for the simulation might be critical when simulating coupled LLG solvers as it is done in this device design. The LLG equation under a spin torque current, being a non-linear one with hysteresis due to the internal field, is sensitive to the trajectory through the phase space. Therefore, the time step should be kept small with high accuracy. This has been achieved in these testbenches using the directive `runlvl=6` and a time step of 0.1ps for GEAR algorithm. This should be adjusted as per requirements of the particular simulation type, simulator engine, and particular algorithm chosen.

6 Summary

We have presented a flexible and powerful approach to modeling of complex spin devices using a Verilog-A based library that allows for inclusion of new phenomena and enhancement of models in a simple plug-and-play approach, thereby removing the complexity of building a monolithic model with multiple physical theories. Further it allows building and testing new device and larger circuit designs completely within SPICE with only a minimal knowledge of spin physics.

The Library is being released as an open source download along with model. It shall also be available as a download from any future functional spin device model and also the Modular Spintronics Library page on nanoHUB.org.

7 Bibliography

1. Datta et al. “Non-volatile Spin Switch for Boolean and Non-Boolean Logic”, Appl. Phys. Lett. 101, 252411 (2012)
2. Ganguly et al. “LibSpin: A Verilog-A/SPICE Library for Spintronics”, TECHCON 2014
3. Srinivasan et al. “Modeling Multi-Magnet Networks Interacting Via Spin Currents”, Handbook of Spintronics, Springer (2013)
4. Hong et al. “Conductance Matrix Approach For Materials with Spin-Hall Effect”, In Prep.
5. Camsari et al. “Modular Approach to Spintronics”, In Prep.

8 Appendix: Module Details

Models for FM, NM, FM-NM

The circuit model of these modules look like a Pi -network as shown in fig. 5. The series represents the usual conductance of the material as one would expect, however, spin currents are not conserved as they travel through a material, as there are always spin-flip phenomena (Dyakonov-Perel and Eliot-Yafet mechanisms) present in materials that decrease the effective spin current magnitude. This decay is characterized by a decay length l_{sf} (spin-flip length).

Additionally, the FM and FM-NM modules polarize spin currents when a charge current current is passed through them. This is characterized by a parameter “ p ” for polarization degree.

For detailed derivation of the models see [3][5]

The conductance matrices for the modules are as below:

NM

$$G_{series} = \frac{A}{\rho L} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & g_{se}^{nm} & 0 & 0 \\ 0 & 0 & g_{se}^{nm} & 0 \\ 0 & 0 & 0 & g_{se}^{nm} \end{bmatrix} \quad G_{shunt} = \frac{A}{\rho L} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & g_{sh}^{nm} & 0 & 0 \\ 0 & 0 & g_{sh}^{nm} & 0 \\ 0 & 0 & 0 & g_{sh}^{nm} \end{bmatrix} \quad (1)$$

Where, $g_{se}^{nm} = \frac{L}{\lambda_{sf}} \operatorname{cosech}(\frac{L}{\lambda_{sf}})$ and $g_{sh}^{nm} = \frac{L}{\lambda_{sf}} \tanh(\frac{L}{2\lambda_{sf}})$. It can be seen that the shunts connections are only for the spin components. This ensures that only the spin signal decays to the ground and the charge conservation is still valid as expected.

FM

$$G_{series} = \frac{A}{\rho L} \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ p & 0 & 0 & g_{se}^{fm} \end{bmatrix} \quad G_{shunt} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & g_{sf} & 0 & 0 \\ 0 & 0 & g_{sf} & 0 \\ 0 & 0 & 0 & \frac{A}{\rho L} g_{sh}^{fm} \end{bmatrix} \quad (2)$$

Where, p is the polarization factor of the ferromagnet, $g_{se}^{fm} = p^2 + (1 - p^2)g_{se}^{nm}$ and $g_{sh}^{fm} = (1 - p^2)g_{sh}^{nm}$.

Direction Dependence of Conduction: The conductance matrices written above can be generalized for a magnet of any arbitrary direction m by rotating the axis of the matrices from z to m using a Unitary transformation $G(m) = R^\dagger G(z)R$. The rotation matrix is constructed to simply rotate the “spin” part of the matrices using the Rodrigues’ rotation formula [3][5].

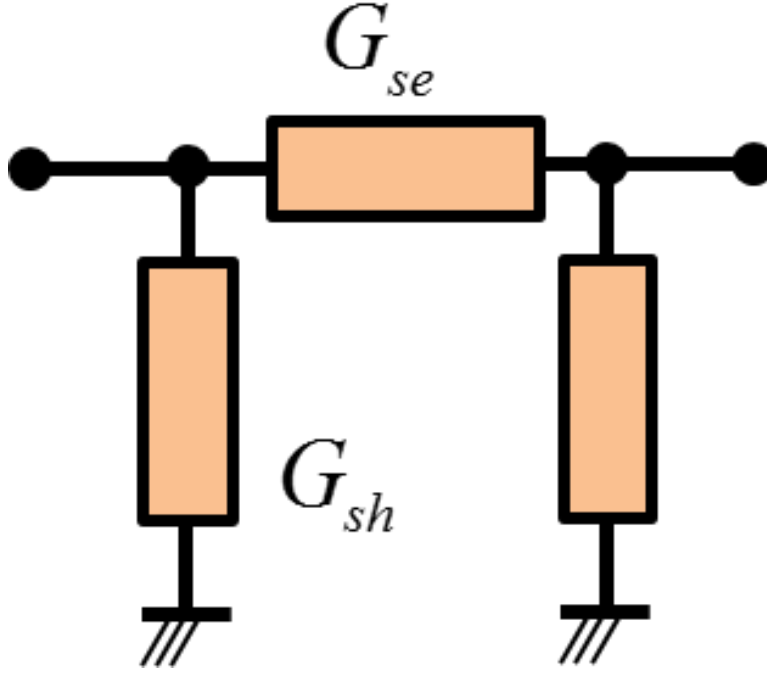


Figure 5: Circuit representation for NM, FM, FM-NM module.

Noting that we want to rotate from $z \rightarrow m$ the full transformation matrix is:

$$R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & u_x^2 + (1 - u_x^2)c & u_x u_y (1 - c) & u_y s \\ 0 & u_x u_y (1 - c) & u_y^2 + (1 - u_y^2)c & -u_x s \\ 0 & -u_y s & u_x s & c \end{bmatrix} \quad (3)$$

Where, $c = m_z$, $s = 1 - m_z^2$, $u_x = \frac{-m_y}{m_x^2 + m_y^2 + m_z^2}$, $u_y = \frac{m_x}{m_x^2 + m_y^2 + m_z^2}$. It can be seen that the charge component in itself does not change by operation with this matrix. The library code calculates the \hat{m} dependent series and shunt conductances using the procedure outlined above.

FM-NM

$$G_{series} = g_0 \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ p & 0 & 0 & 1 \end{bmatrix} G_{shunt} = g_0 \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & sl & -fl & 0 \\ 0 & fl & sl & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

Where, g_0 is the ballistic conductance of the interface. The sl and fl stand for the ‘‘Slonckzewski’’ and ‘‘Field-Like’’ spin torque conductances and give the transverse spin currents on the ferromagnet that apply a spin torque on it. For ohmic (metallic) interfaces $fl \approx 0$ and $sl \approx 1$ (as observed experimentally). The conductances could be generalized to any arbitrary direction using the same procedure described for FM.

Model for GSHE

The GSHE module is implemented as two coupled branches, one for the charge direction between nodes 1 and 2 and a spin branch between nodes 3 and 4. The circuit model is as shown in fig. 6. It can be seen that the charge branch has only a series conductance with current sources for inverse spin Hall effect, while the spin branch (with dotted red terminals) has both series and shunt conductances along with current sources for the spin Hall effect.

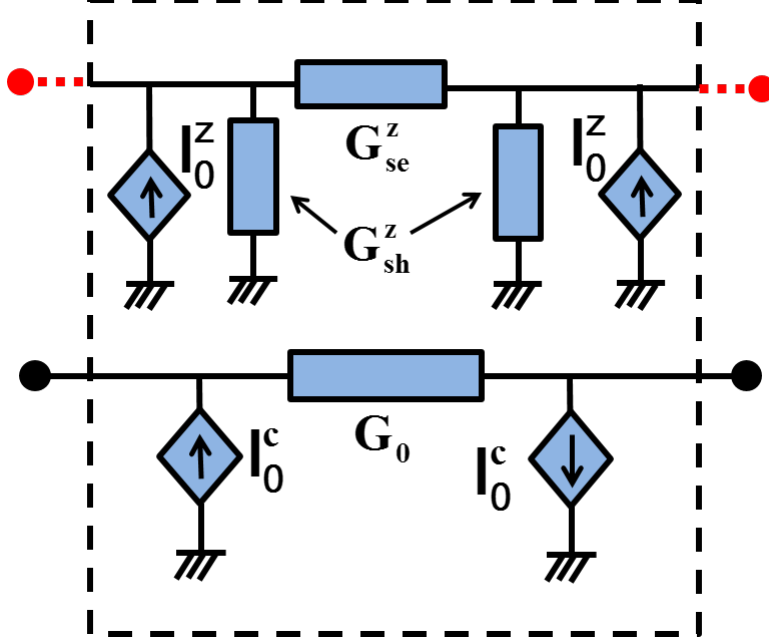


Figure 6: Circuit representation for the LLG module.

The conductances and current source strengths are given as:

$$G_{se}^s = \frac{L_{det}W_{det}}{\rho\lambda_{sf}} \operatorname{cosech}\left(\frac{t_{inj}}{\lambda_{sf}}\right) \quad (5)$$

$$G_{ss}^s = \frac{L_{det}W_{det}}{\rho\lambda_{sf}} \tanh\left(\frac{t_{inj}}{2\lambda_{sf}}\right) \quad (6)$$

$$G_{se}^c = \frac{W_{inj}t_{inj}}{\rho L_{inj}} \quad (7)$$

$$\beta = \frac{\theta_{sh}L_{det}}{t_{inj}} \quad (8)$$

$$I_0^s = \beta G_{se}^c (V_1 - V_2) \quad (9)$$

$$I_0^c = \beta G_{se}^c (V_3 - V_4) \quad (10)$$

Where θ_{sh} is the spin Hall angle, ρ is the resistivity, λ_{sf} is the spin flip length and rest are geometrical dimensions. For detailed derivation see [4][5].

Model for MTJ

This module represents a simple MTJ and accounts for TMR, in-plane and out-of-plane torques and any external spin current excitation.

The model equations are:

$$G_{cc} = g_0(1 + P_1P_2\hat{m}_1 \cdot \hat{m}_2) \quad (11)$$

$$I_{s1} = ag_0P_2V_2\hat{m}_2 - bg_0(P_1V_1 + P_2V_2m_1 \hat{\times} m_2) \quad (12)$$

$$I_{s2} = ag_0P_1V_1\hat{m}_1 + bg_0(P_1V_1 + P_2V_2m_1 \hat{\times} m_2) \quad (13)$$

The external spin excitation is just shunted to ground through a large conductance g_{sh} which is an adjustable parameter. The spin currents and the external excitation is provided to the LLG Solver module through the terminals s1 and s2.

Model for LLG

Dynamics of the free-layer ferromagnet (FM) is an essential part of the complete operation of spintronic circuits. Accurate modeling of magnet dynamics is critical to evaluate device performance parameters such as switching time, switching energy, frequency of oscillation etc. when designing a spintronic switch or an oscillator. The dynamics of a monodomain ferromagnet under the action of a magnetic field and spin torque is given by the following Landau-Lifshitz-Gilbert equation:

$$\frac{(1 + \alpha^2)}{\gamma H_k} \frac{d\hat{m}}{dt} = -\hat{m} \times \mathbf{h} - \alpha \hat{m} \times \hat{m} \times \mathbf{h} - \hat{m} \times \hat{m} \times \mathbf{i}_s - \alpha \hat{m} \times \mathbf{i}_s \quad (14)$$

Where, \vec{h} is the sum of all magnetic fields, \vec{i}_s is the spin current (scaled by $\frac{h}{2qM_s\Omega}$), and \hat{m} is the instantaneous magnetization of the ferromagnet. All the RHS contribution terms are normalized w.r.t. the magnitude of the coercive field H_k .

Since our goal is to solve the spin circuit completely within SPICE, we create an LLG solver circuit that is modular and extensible (to include any number of input magnetic field, spin currents, and noise) using an integrator circuit that instantaneously calculates the state of the magnetization of the ferromagnet. This Magnet-Dynamics solver element is then connected to the the appropriate ferromagnet in the circuit, providing a self-consistent simulation of spin-transport and magneto-dynamics, thereby obtaining the full transient response of the circuit.

The module implemented in the library is a noiseless monodomain LLG solver whose ports are s, h, and m. The port s is used to provide the spin torque, h is used to provide an externally applied magnetic field and port m is the out magnetization. The input spin torque and magnetic fields are provided using controlled voltage sources as shown in fig. 7. The parameters to the module are coefficients to construct the internal magnetic field from the magnetization (Kx, Ky, Kz), damping coefficient (alpha) and material parameters like M_s (saturation magnetization), H_k .

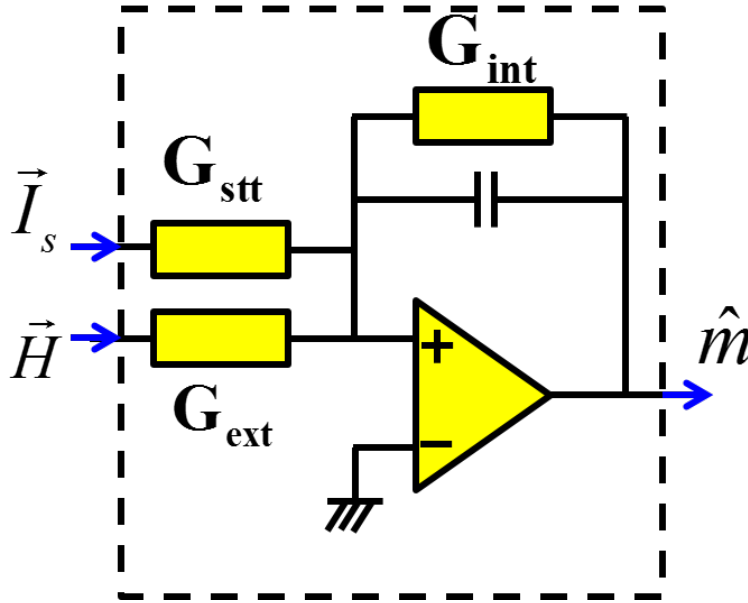


Figure 7: Circuit representation for the LLG module.

The circuit solver is composed of an ideal OPAMP based integrator circuit (fig. 7). The feedback loop constructs the internal magnetic field, while the external stimulus such as applied magnetic field and spin torque are connected directly to the + terminal of the OPAMP. In an ideal OPAMP, no current flows in the input node while the voltage at the + node is 0 (as the - node is grounded), therefore the sum of the current

contributions through the conductances is same as the current flowing through the capacitor. At the + node of the opamp, we can write using KCL:

$$C_{dyn} \frac{d(0 - V_m)}{dt} = G_{int} V_m + \sum G_i V_i \quad (15)$$

Which has the same form as the LLG equation. Therefore the output voltage of the OPAMP gives the solution of the LLG equation. All the conductances are V_m dependent and are defined to perform the necessary vector algebra for each of the stimuli, as they enter in the LLG equation. As an example, conductance for spin transfer torque is given by:

$$G_{stt} = \hat{m} \times \hat{m} + \alpha \hat{m} = \begin{bmatrix} -m_y^2 - m_z^2 & m_x m_y & m_x m_z \\ m_x m_y & -m_x^2 - m_z^2 & m_y m_z \\ m_x m_z & m_y m_z & -m_x^2 - m_y^2 \end{bmatrix} + \alpha \begin{bmatrix} 0 & -m_z & m_y \\ m_z & 0 & -m_x \\ -m_y & m_x & 0 \end{bmatrix} \quad (16)$$

Magnetic Coupling

The magnetic coupling module is used to generate the mutual magnetic field between any two magnets. The model is implemented as voltage controlled voltage sources (VCVS) because the magnetic coupling between two magnets i and j is given as:

$$\begin{Bmatrix} H_x \\ H_y \\ H_z \end{Bmatrix}_j = \begin{bmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{bmatrix}_{ji} \begin{Bmatrix} m_x \\ m_y \\ m_z \end{Bmatrix}_i \quad (17)$$

The parameters for the modules are the coefficients K_{xx} etc. The circuit module is as shown in fig. 8.

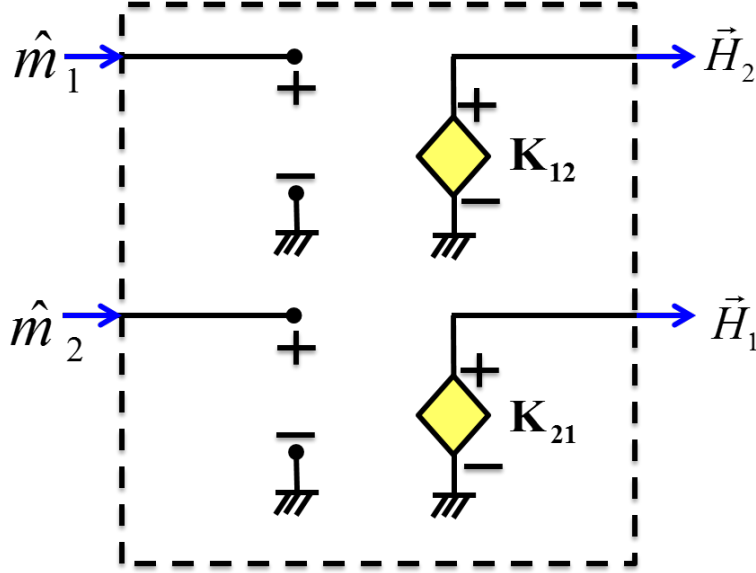


Figure 8: Circuit representation for the Magnetic Coupling module.