

OOMMF MODELLING OF MAGNETIZATION DYNAMICS IN MICROMETER SIZED STRUCTURES FOR SENSING APPLICATIONS

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Abstract: *A software 2D micromagnetic simulator (OOMMF - Object Oriented Micromagnetic Framework) was used to simulate magnetization curves and show the evolution of magnetic domains for a Permalloy (Ni₈₀Fe₂₀)-based thin film. A comparison between different Simulmag and OOMMF software solutions is made. This paper is intended to serve as a guide in the software simulation of magnetization dynamics in micrometer sized structures with OOMMF while also reaching some essential conclusions regarding the development of sensing applications using associated magnetic effects. Simulation results are joined and confirmed by some experimental data.*

Key words: *thin films, hysteresis loop, micromagnetic simulation, magnetic domains, Landau-Lifshitz-Gilbert (LLG) equation.*

1. Introduction

Magnetization dynamics of thin films is a crucial research topic necessary in the development of novel technologies including sensors, oscillators, various types of magnetic memories like Spin-Transfer Torque MRAM or Spin Orbit Torque MRAM [5] and other applications that have a focus on spintronics. In this regard, the software simulation of micromagnetic structures is a vital step. Although there are plenty of free software that simulate single domain structures, there are significantly less choices for multi-domain structures and they typically come at a great cost or require specific hardware. In terms of free solutions, the Object Oriented Micro Magnetic Framework (OOMMF) project developed by Information Technology Group inside National Institute of Standards became a standard solution for micromagnetic simulations due its performance, stability and portability. The object oriented micromagnetic framework (OOMMF) has been developed by Mike Donahue and Don Porter in the National Institute of Standard and Technology. The program is based on C++ with Tcl/Tk.

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2. Theoretical Aspects

Various technological applications are explored by phenomena like the planar Hall effect (PHE), anisotropic magnetoresistance effect (AMR) giant magnetoresistance effect (GMR) or tunneling magnetoresistance effect (TMR) that magnetic thin films and nanostructured magnetic systems are exhibiting.

In practice it was observed that if a magnetic material is introduced in magnetic field of a certain direction and whose intensity is gradually and slowly increasing, the resultant magnetization progressively increases until it is reaching the saturation value [5].

Systems with hysteresis behaviour are nonlinear, and can be mathematically challenging to model. Some phenomenological models like the Preisach model [1] or the Jiles-Atherton model are used to describe at macroscopic scale the hysteresis curves of ferromagnetic materials. However, these models fail in describing the behaviour at microscopic scale, the existence of the magnetic domains and the mechanism of magnetization in thin films and magnetic multilayers [4].

OOMMF is based on the solution of the Landau-Lifshitz-Gilbert (LLG) equations as applied to *finite elements* into which the material to be simulated is divided. OOMMF discretizes the sample using a grid of cubic cells of a size given by the user and considers a uniform magnetization inside each cell. This process can be done automatically for virtually any shape provided by the user.

Depending on the solver used in the simulation, OOMMF will either find equilibrium configurations or the time dependence of the magnetization by using a time discretized version of the LLG equations applied to every cell.

The equilibrium magnetization configuration results from the minimization of the system's free energy. The energy of a ferromagnetic system (as modeled in the software) is composed of: the mean field exchange energy E_{ex} between nearest neighbors characterized by the exchange coupling constant A (J/m); the magnetocrystalline anisotropy energy, which describes the interaction of the magnetic moments with the crystal field characterized by the constant K_1 (J/m³); the damping parameter α is not well known. Values of α between 0.005 and 2.0 have been used to solve LLG. The damping parameter was not found to change the equilibrium magnetization configurations indomain walls in uniform ferromagnetic systems [2]. The LLG equation used is:

$$\frac{d\vec{M}}{dt} = -\frac{\gamma}{1+\alpha^2} \vec{M} \times \vec{H}_{eff} - \frac{\gamma\alpha}{(1+\alpha^2)M_s} \vec{M} \times (\vec{M} \times \vec{H}_{eff}). \quad (1)$$

where t is time, γ is the precession factor, α is the damping factor \vec{H}_{eff} is the total effective field acting on the magnetization and, \vec{M} is the magnetization.

In this equation both left and right side, there are the time derivative terms of magnetization ($d\vec{M}/dt$). Since the LLG equation is a nonlinear differential equation, it cannot be solved for most geometries analytically.

From this point of view, the finite difference method (FDM) with equivalent rectangular or cubic cells and a certain discrete time step are employed. OOMMF is based on the FDM. There are various algorithms to solve the LLG equation numerically (e.g. Runge-Kutta method of fourth order).

2.1. Starting OOMMF and Configuring a Simulation

Once installed, OOMMF works much the same in Windows and Linux, but there are some differences in which files we need to download and the install procedures we go through. In both cases we need to get OOMMF and the appropriate tcl/tk for our system. For full install instructions please see [6]. Figure 1 shows the initial menu at program start.

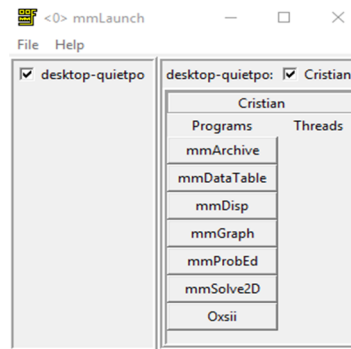


Fig. 1. OOMMF initial steps

This gives a menu of options: mmArchive: to auto-save scalar and vector field data; mmDataTable: to display current values of scalar outputs; mmDisp: to display vector fields; mmGraph: to form x-y plots; mmProbEd: to view or modify a problem for mmSolve2D or Oxsii; mmSolve2D: to control the 2D solver; Oxsii: to control the 3D solver. A detailed description of each library as well as a quick setup guide is given in the OOMMF user guide [6].

The graphical interface of the software solver allows the setting of the main parameters of the LLG equation as well as the physical dimensions of the mask to be simulated (Figure 2 shows necessary tabs to configure for a simulation). You can import a 2D image (some examples are in Figure 3) or use a predefined shape as shown below.

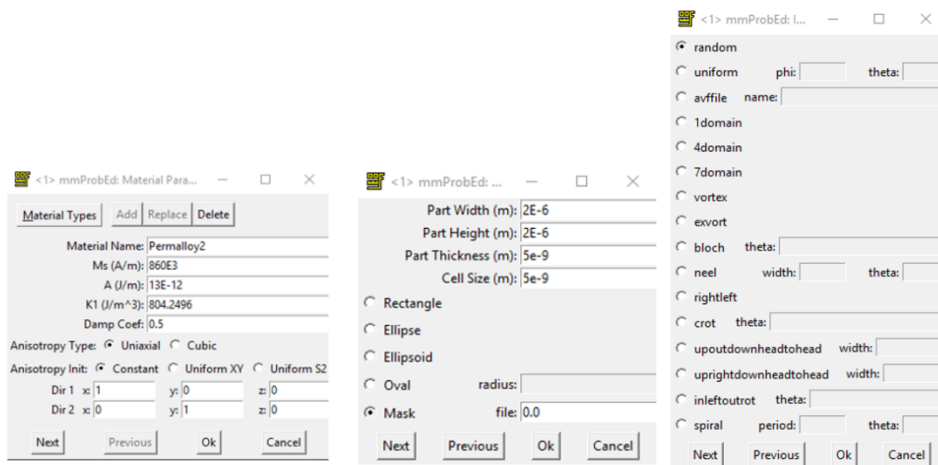


Fig. 2. mmProbEd (from left to right): Material Parameters, Part Geometry and Initial magnetization tabs



Fig. 3. Masks which were used for Hall Sensors Simulations. The image should be in black/white format to be accepted by the simulator (during simulation the black regions will represent the magnetic material)

The initial magnetization tab allows setting of various initial magnetization conditions for the specified object and helps the solver find the solutions when simulation starts. Moving on to the Experiment Parameters tab, we can specify up to 10 field ranges (i.e. cycles of field variation) for each individual direction (example in Figure 4).

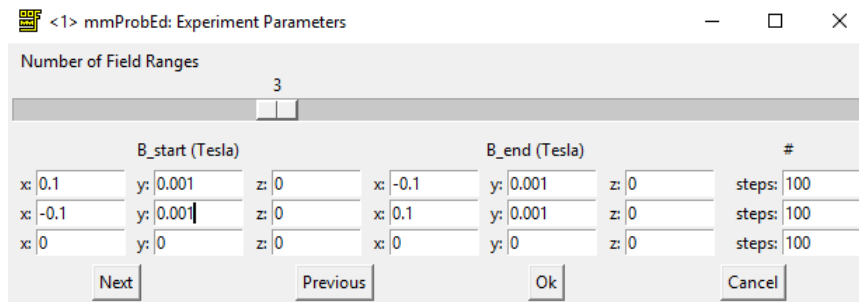


Fig. 4. Experiment Parameters

After setting up all the desired parameters and conditions in mmProbEd, in order to successfully gather essential data from one simulation, three extra windows are recommended: mmDisp, mmGraph and mmSolve2D. By opening the mmSolve2D we can load the Problem and can select where the simulation will output data (in our case mmGraph and mmDisp) after which we can start the simulation (see [7] for further details).

2.2. Motivations for Choosing Certain Simulation Parameters

In micromagnetic simulation, to obtain reliable simulation results, the cell size should be smaller than the exchange length l_{ex} (the software considers the dimension of a cell to be single magnetic domain). In the case of Permalloy, the exchange length (the relative strength of exchange and self-magnetostatic energies) is given by:

$$l_{ex} = \sqrt{\frac{2A}{\mu_0 M_s^2}} = \sqrt{\frac{2 \times 1.3 \times 10^{-11}}{4\pi \times 10^{-7} \times (8 \times 10^5)^2}} \approx 5.68 \text{ (nm)}. \quad (2)$$

Thus, a cell size of 5 nm is more than enough to ensure reliable results (even 10 nm may be sufficient according to some literature). By tests, the user can find an optimal cell size.

The part geometry was mostly chosen due to simulation time constraints. A simulation like this can easily take from a couple of hours to days depending on the parameters and system size keeping in mind physical dimensions - μm - of a spintronic sensor. In our case, the initial magnetization is assumed to be “uniform” and was set with angle phi (on the x axis) at 5 degrees and angle theta (on z axis) at 0 degrees - this was done to aid the initial rotation of magnetic moments at the beginning of the simulation.

3. Experimental Setup and Simulations

3.1. Schematic of a Planar Hall Effect Sensor

The planar Hall sensor measures the change in anisotropic magnetoresistance caused by an external magnetic field in the Hall geometry. This name is given because the sensor responds to magnetic field components in the sensor plane as opposed to the ordinary Hall sensor, which measures field components perpendicular to the sensor plane. The schematic of a PHE sensor can be viewed in Figure 5 [3].

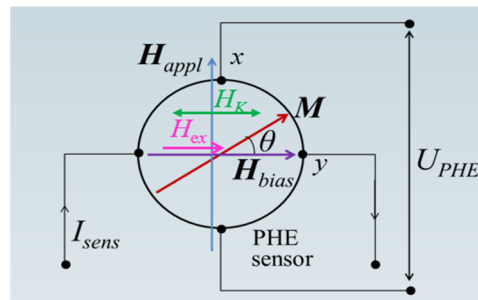


Fig. 5. Schematic of a PHE sensor system

H_K is the anisotropy field and H_{ex} is the exchange field.

The planar Hall effect voltage (U_{PHE}) and sensor sensibility (S_H) for exchange biased structures are given by (note that the constant C can vary depending on the setup):

$$U_{PHE} = C \cdot M^2 \cdot j \sin 2\theta, \quad (3)$$

$$S_H \sim \frac{1}{H_K + H_{ex}}. \quad (4)$$

Remark that the PHE signal can be used as probe of magnetization reversal processes.

3.2. OOMMF Simulations and Simplifying Computing of the Planar Hall Effect Voltage

Figure 6 illustrates a comparison between a single domain approach (using Simulmag [8]) and multi-domain structure simulation (using OOMMF) of the PHE response when the magnetic field is applied over the hard axis of magnetization, like in Figure 5. The simulated structure is a Permalloy square with $250 \times 250 \text{ nm}^2$, 10 nm thick. These are qualitative results and emphasise the difference between single and multi-domain approaches.

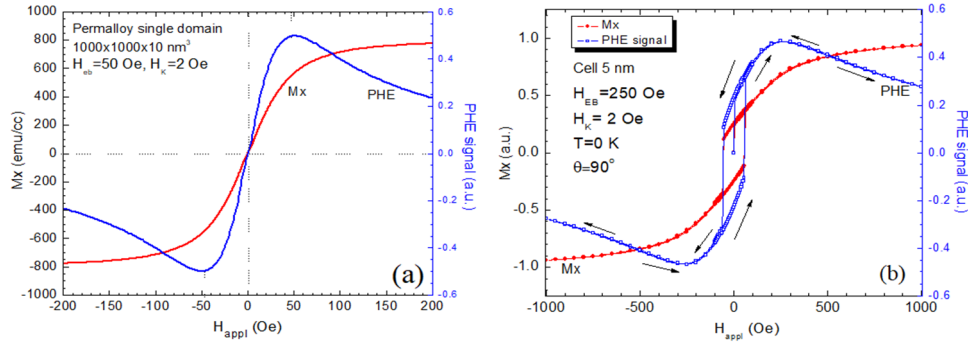


Fig. 6. (a) Single Domain (Simulmag) and (b) Multi-Domain (OOMMF) simulation of the PHE response of a square plate of Permalloy film

Regarding the performed OOMMF simulations, a pattern was observed which leads to a very accurate approximation of the U_{PHE} (take into account the schematic in Figure 5):

$$U \sim M^2 \sin 2\theta, \quad (5)$$

$$M = \sqrt{M_x^2 + M_y^2}. \quad (6)$$

After substituting (6) into (5) and some simple trigonometric transformations we obtain:

$$(M_x^2 + M_y^2) \cdot \frac{M_x}{\sqrt{M_x^2 + M_y^2}} \cdot \frac{M_y}{\sqrt{M_x^2 + M_y^2}} = M_x \cdot M_y. \quad (7)$$

Moving on to some OOMMF simulations: a varying magnetic field was applied over the X axis (from 0.1T to -0.1T) and a constant (polarization) field is applied over Y axis being, alternately, 0 T, 0.001 T, 0.002T and 0.005T. All simulations were performed on all type of objects shown in Figure 3. Just one object for each variation in applied field is presented. Note that each figure will contain a magnetization or U_{PHE} graph as well as a capture of the object during a specific magnetization state (from which the domain walls can easily be seen). Notice the fringe magnetic fields in Figure 7 in the initial state (the green lines on the margin represent the opening and closing of magnetic field lines).

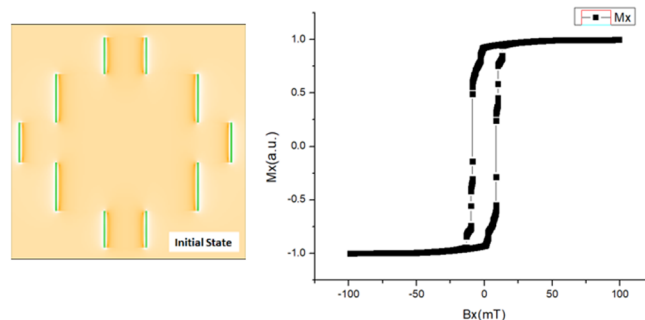


Fig. 7. Hysteresis curve obtained from simulation (B_x variable, $B_y = 0$)

Notice the perpendicular magnetic field in the coercivity state (Bloch domains-shown by the color green) in both Figure 9 and Figure 10 (not present in Figure 8). Surprisingly the perpendicular field is stronger in the coercivity state at a B_y field of 0.002T.

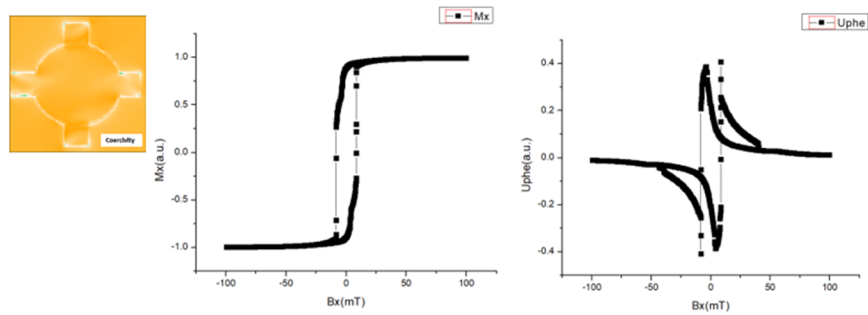


Fig. 8. Hysteresis curve and U_{PHE} obtained from simulation (B_x variable, $B_y = 0.001T$)

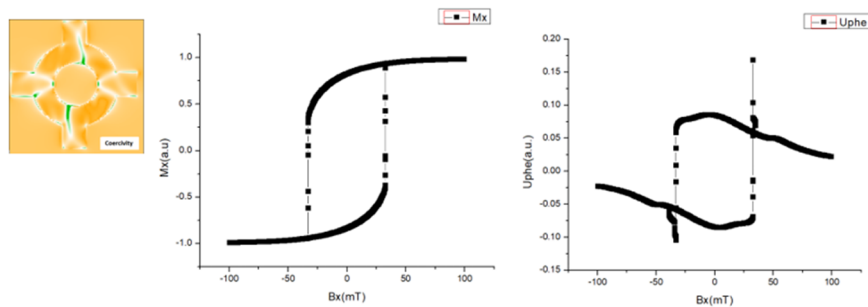


Fig. 9. Hysteresis curve and U_{PHE} obtained from simulation (B_x variable, $B_y = 0.002T$)

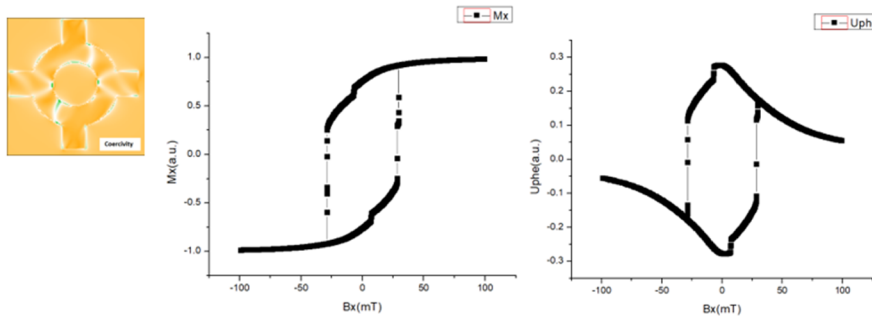


Fig. 10. Hysteresis curve and U_{PHE} obtained from simulation (B_x variable, $B_y = 0.005T$)

3.3. Experimental Results

Two typical experimental results on PHE measurements (see the setup from Figure 5) are presented in Figure 11a (when the magnetic field, H_{appl} , is directed over the hard axis of magnetization) and in Figure 11b (when the magnetic field, H_{appl} , is directed over the easy axis of magnetization). The samples were deposited at SPINTEC-Grenoble and characterized at our University. Comparing Figure 11a with simulation results from

Figure 6 we can see that the single domain approach can describe very well the field dependence of the PHE but cannot predict the small hysteretic effect which is highlighted by the multi-domain approach. The measurements from Figure 11b are well described (qualitatively) by the simulations presented in Figure 8 where the system is subject to a low biasing field.

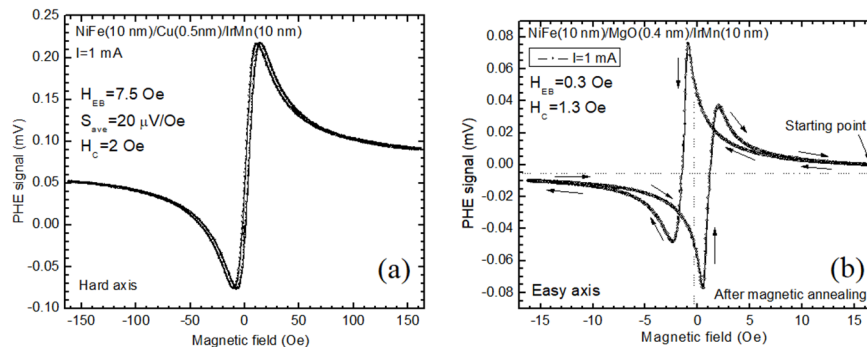


Fig. 11. PHE dependences when the magnetic field is applied (a) over the hard axis of magnetization and (b) over easy axis of magnetization

4. Conclusions

Basic aspects on using OOMMF for micromagnetic simulations are presented in this paper. Because the simulator calculates the interaction at nanometric scale, it can be used for fundamental studies on magnetization dynamics in different nano or micro-structures providing a solid base for future development of various applications like sensing, magnetic memories, nano-oscillators etc. The simulations presented in this paper are in good agreement with experimental data. The nucleation of magnetic domains and their behavior during the switching process can be studied as well. Some results are illustrated in Figures 7-10. However, the micromagnetic approach is not feasible for large systems because of the very large number of cells and huge computing demands. Other simulators, like COMSOL Multiphysics, based on Maxwell's equations, can be used in this case.

References

1. Della Torre, E.: *Magnetic Hysteresis*. IEEE Press, New York, 1999.
2. Hubert, A., Schäfer, R.: *Magnetic Domains: The Analysis of Magnetic Microstructures*. Springer, 2009.
3. Prados, C., et al.: *Extraordinary Anisotropic Magnetoresistance Effect under 35 Oe Field at Room Temperature in Co/Ni Multilayers*. In: *Applied Physics Lett.* **67** (1995), p. 718.
4. Preisach, F.: *Über die magnetische Nachwirkung*. In: *Z. Physik* **94** (1935), p. 277-302.
5. Prenat, G., Jabeur, K., et al.: *Beyond STT-MRAM, Spin Orbit Torque RAM SOT-MRAM for High Speed and High Reliability Applications*. In: Zhao W., Prenat G. (Eds.) *Spintronics-Based Computing*. Springer, Cham.; Online ISBN 978-3-319-15180-9, 2015.
6. Scheinfein, M.R., Price, E.A.: *LLG Micromagnetics Simulator Manual v4.01*, 2015, p. 34.
7. http://math.nist.gov/oommf/doc/userguide12a5/userguide/Basic_Installation.html.
8. <https://math.nist.gov/oommf/contrib/simulmag/>.