doi:10.1017/S1431927622006730
Microsc. Microanal. 28 (Suppl 1), 2022

Micromagnetics Simulation as a Supplement to and Diagnostic for Lorentz Transmission Electron Microscopy

Jacques Reddinger[1*] and Will Parker[1]

[1.] University of Oregon, Department of Physics, Eugene, OR, USA.
*Corresponding author: jacquesr@uoregon.edu

Lorentz Transmission Electron Microscopy (LTEM) is a valuable tool in the study of thin-film nanoscale magnetic phenomena. As the incident electron beam passes through a sample, the in-plane components of the sample's magnetization deflect electrons via the Lorentz force. The resulting fluctuations in intensity due to the induced diffraction contrast allows imaging of the sample's local magnetic structure. Since the mechanism behind this process is well understood, the in-plane magnetization can be calculated. But LTEM is not without its limitations.

Although LTEM is used on thin-films, there is still interest in the details of the 3D structure of magnetic materials which cannot be resolved using LTEM. Additionally, LTEM cannot recreate the out-of-plane component of the magnetization, losing further detail of micromagnetic structures. Finally, as with any complex instrument, the more diagnostic tools available, the better. By having another way to produce an LTEM image, the user can qualitatively/phenomenologically compare these images with those produced by their equipment to verify their experimental setup and potentially realize new discoveries.

Just as an LTEM image can be used to simulate the in-plane magnetization, via the same mechanism the in-plane magnetization can be used to produce a simulated LTEM image. Mumax3, a micromagnetic simulation program developed by Ghent University's DyNaMat group, is effective in simulating the magnetization of FeGd multilayers in experimental conditions [1]. Additionally, we have produced a simulation that creates an LTEM image from a 3D array of magnetization.

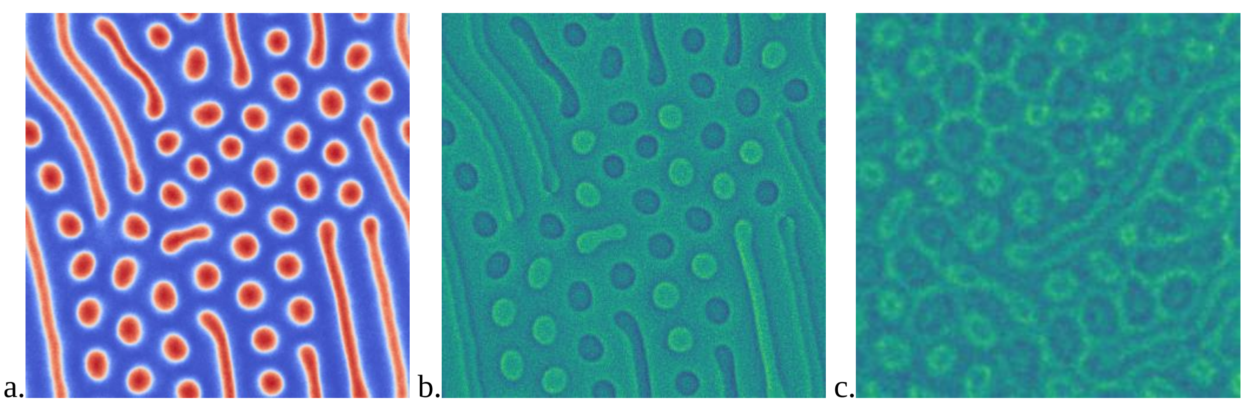

Figure 1. a. Simulated magnetization of skyrmions in FeGd multilayers, b. Simulated LTEM image from magnetization, c. Data collected from LTEM (Image size 1 x 1 um)

We are currently using LTEM and to characterize the formation process of Magnetic Skyrmions on FeGd multilayers. Additionally, while these samples are only 80 nm thick, we have interest in the details of the 3D structure and out-of-plane magnetization of Magnetic Skyrmions which cannot be resolved using LTEM. All of this has motivated the use of micromagnetic simulation as a supplement and diagnostic for Lorentz Microscopy.

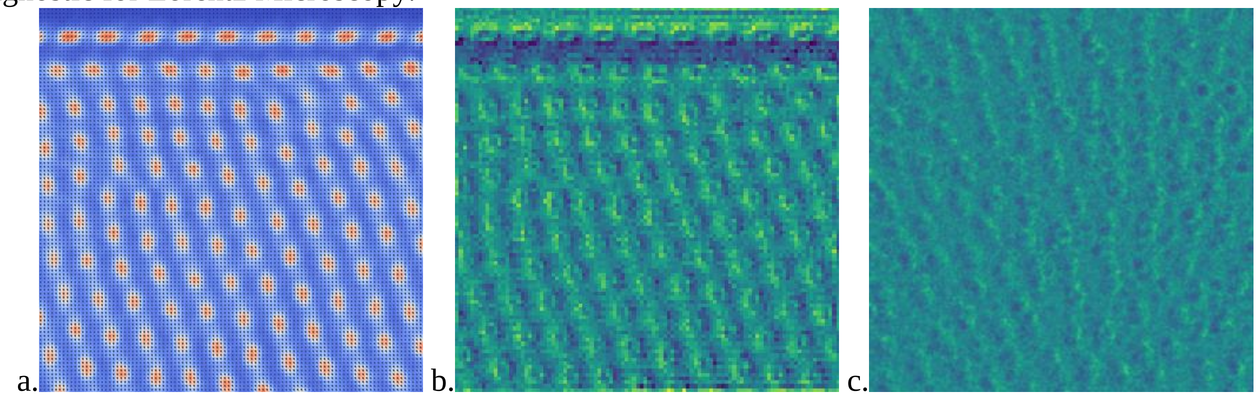

Figure 2. a. Simulated magnetization of magnetic bubbles in FeGd multilayers, b. Simulated LTEM image from magnetization, c. Data collected from LTEM (Image size 1 x 1 um)

In our particular use case, FeGd is deposited on a "holey" silicon nitride. It is important to note that the simulation only considers 2 x 2 holes, whereas the sample consists of dozens. The sample undergoes a field sweep to -400 mT to 150 mT. In the data, this generates domain walls and an initially unrecognized magnetic structure. In simulation, this forms domain walls that collapse into magnetic bubbles. Upon generating the simulated LTEM image, it becomes clear that the unrecognized magnetic structures are in fact magnetic bubbles. At this point in the simulation, there are no surviving domain walls, so phenomenological differences have already started. This suggests that the impact of boundary conditions combined with the interaction range of these magnetic structures is large enough to impact skyrmion formation for sufficiently small samples. In future work, it would be valuable to reperform these simulations with varied in-plane magnetic fields to rule out stray magnetic fields as a potential cause for these effects.

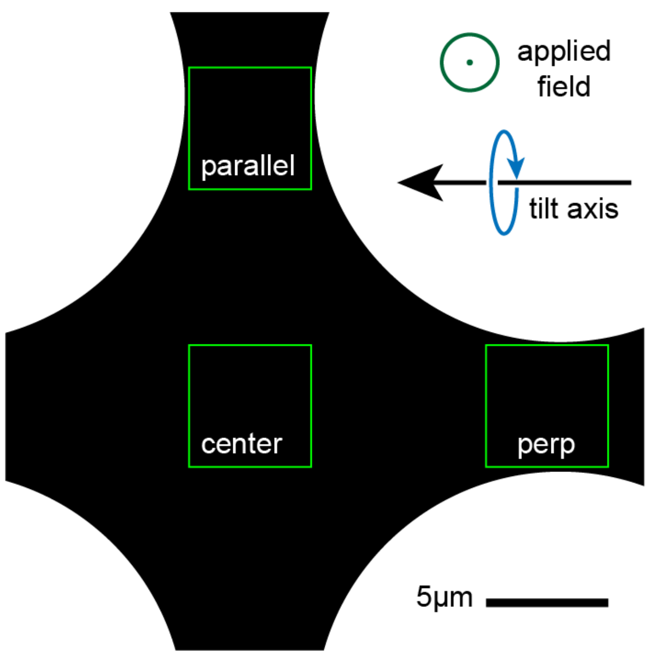

Figure 3. Diagram of FeGd on silicon nitride substrate under external magnetic field

https://doi.org/10.1017/S1431927622006730 Published online by Cambridge University Press

After the field sweep, the sample is then tilted to 22 degrees, back to 0 degrees, then to -22 degrees. As this happens, in the data, skyrmions form on one side of the perpendicular region and translate towards the other side, wrapping around the hole and heading towards the parallel region before "sloshing" back during the return tilt. In simulation, as the tilt increases, bubbles start to disappear in the parallel region until the sample magnetization is fully saturated. Notice the parallels between how magnetic structures "slosh" between the two regions. While there is a disparity near the edges, in certain regions, the formation of magnetic structures agrees with simulation. For example, far from the holes in the center region the sample behaves as if it were square.

Using simulation in conjunction with data collected with LTEM has offered further insight into the nature of skyrmion formation in FeGd multilayers. Beyond just clarifying some questions we had about our data, it has also produced insight on the impact of sample geometry on skyrmion formation as well as additional research questions [2].

[1] Arne Vansteenkist et al., AIP Advances **4** (2014), p. 107133 doi:10.1063/1.4899186

[2] This material is based upon work supported by the National Science Foundation under Grant No. 2012191.

https://doi.org/10.1017/S1431927622006730 Published online by Cambridge University Press