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Review Report on PhD Thesis

Faculty: **Central European Institute of Technology Brno University of Technology in Brno** Academic year: **2021/2022**

Student: **Ing. Igor Turčan**

Doctoral study program: **Advanced Materials and Nanosciences**

Field of study: **Advanced nanotechnologies and microtechnologies**

Supervisor: **Ing. Michal Urbánek, Ph.D.**

Reviewer: **Dr. Denys Makarov**

PhD thesis title: Magnetism in curved geometries

Topicality of doctoral thesis:

As the title suggests, the thesis concerns the emerging topic of curvilinear magnetism with a focus on static and dynamic magnetization studies in magnetic thin films and stripes prepared on corrugated surfaces.

The research field of curvilinear magnetism is rather new. Although geometrical curvature attracted attention of the magnetism community back in 1990s with the work of the group of Avadh Saxena [Physical Review Letters 74, 813 (1995)], the topic matured after the pioneering work by Yuri Gaididei et al. [Physical Review Letters 112, 257203 (2014)] and the term „curvilinear magnetism" was introduced in 2016 in the review paper on magnetism in curved geometries by Streubel et al. [J. Phys. D: Appl. Phys. 49, 363001 (2016)]. At present, the concept of curvilinear magnetism is actively explored by physicists and material scientists as it provides an appealing possibility to tailor magnetic responses (anisotropic and chiral) relying on the change of geometric curvature of thin films [Adv. Mater. 34, 2101758 (2022)] and wires [Small 18, 2105219 (2022)]. This method is complementary to the classical material screening approach aiming to adjust magnetic responses for specific applications. In particular, it is possible to show that geometrically curved low dimensional magnetic architectures prepared of intrinsically *achiral* magnetic materials (say, Permalloy), can reveal magnetochiral responses [Physical Review Letters 123, 077201 (2019)]. There are numerous appealing concepts of using curvilinear thin films for the stabilization of homochiral domain walls, curvature-induced skyrmions and skyrmionium states. In addition to magnetization statics, there are exciting proposals of using curved architectures for high-speed racetracks based on domain walls and spinwave filters. Recently, the concepts of 3D magnonics [Gubbiotti, G., ed.: Three-Dimensional Magnonics: Layered, Micro- and Nanostructures.

Jenny Stanford Publishing (2019)] as well as flexible magnonics [Journal of Applied Physics 130, 150901 (2021)] were put forth exploring advantages offered by 3D and curvilinear architectures for the design of prospective magnonic devices.

In his PhD thesis, Mr. Turčan synergistically addressed both statics and dynamics of geometrically curved magnetic thin films. The thesis are organized as follows:

1) chapter I introduces relevant theoretical concepts, which are needed to understand the discussions in the thesis. In particular, much attention is given to the description of the magnetic energy functional, magnetization reversal, (linear) magnetization dynamics and related damping as well as geometry-induced magnetic anisotropy.

2) chapter II summarizes fabrication methods to prepare magnetic thin films (e-beam evaporation), structuring of the samples using electron beam lithography and direct writing of curvilinear templates using FEBID. Related topics of the interaction of electrons with solids are addressed as well.

3) chapter III offers an overview of the characterization methods used for the investigation of the magnetic properties of the samples. In particular, magnetooptical microscopy is introduced together with different methods applied for the characterization of magnetization dynamics including BLS and VNA-FMR.

4) chapter IV presents the actual results of the thesis including preparation of corrugated templates, deposition and patterning of magnetic thin films, static characterization of the samples using VSM and MOKE, dynamic characterization of the samples using BLS and VNA-FMR.

5) the thesis are summarized with a conclusion section.

Meeting the goals set:

In his PhD thesis, Mr. Turčan has the following goals:

1) fabricate corrugated substrates with large amplitude of corrugations and their small period. For achieving this goal, Mr. Turčan explored two methods. The first one is based on FIB irradiation of GaAs substrates, which does result in a periodic template of sinusoidal shape with a period down to 200 nm and an amplitude of about 10 nm. These templates appeared to be too shallow to study effects of geometry induced magnetic anisotropy in corrugated magnetic thin films. Therefore, Mr. Turčan focused on the direct writing of SiOx nanostripes using FEBID. Detailed optimization of the process allowed Mr. Turčan to fabricate periodic stripe arrays of sinusoidal shape with periodicity down to 40 nm and amplitude up to 25 nm. The demonstrated advantage of using FEBID is the possibility to tune the amplitude of the pattern and its periodicity independently. With the fabrication of nanoscale periodic patterns using FEBID, Mr. Turčan successfully achieved this goal.

2) prepare magnetic thin films on corrugated templates and understand static magnetic properties of the samples. Mr. Turčan developed skills to fabricate high quality NiFe thin films (thickness of 10 nm) on templates prepared by FEBID. The deposition was carried out using e-beam evaporation. The films were lithographically patterned in geometries of interest (disks, stripes) using EBL. Relying on MOKE microscopy, Mr. Turčan studied magnetic hysteresis loops, determined easy (perpendicular to the

corrugation direction) and hard (parallel to the corrugation direction) axes of magnetization. The study included corrugated samples (different amplitude and periodicity of corrugation) and the reference sample prepared on planar substrate. The experimental work was carried out at the high technical level and experiments were well thought through. For instance, to minimize the effect of the shape anisotropy, Mr. Turčan patterned his samples in a disk-shaped structures. In addition to the determination of the constant of the geometry induced magnetic anisotropy based on MOKE data, Mr. Turčan applied integral magnetometry measurements using VSM to determine the saturation magnetization of the samples. An important fundamental outcome of this part of the thesis is the determined scaling dependence of the geometry induced anisotropy on the amplitude of corrugations (for their constant period). With these results, Mr. Turčan successfully completed this goal.

3) study the magnetization dynamics of corrugated FeNi thin films. Magnetization dynamics were excited using microstrip antenna and spin waves were measured using BLS. The measurements were carried out of stripe-shaped samples with and without corrugations. The corrugation direction was set to be perpendicular to the stripe axis. This brought complications in the comparison of the BLS data for the corrugated samples and the reference sample. In the latter case, the easy axis of magnetization was along the stripe axis while for the corrugated samples, the easy axis was perpendicular to it. Mr. Turčan solved this problem in a very elegant way by applying in-plane magnetic field orthogonal to the stripe axis for the case of the reference sample. When the strength of the applied magnetic field matched the anisotropy field due to corrugations, the BLS maps of the reference and corrugated samples became comparable. The BLS data allowed Mr. Turčan to analyze the propagation length of spin waves in the samples. Mr. Turčan determined that the increase of the corrugation amplitude results in the decrease of the propagation length. This result was correlated with the VNA-FMR data, which provided access to the change of the damping parameter as function of the corrugation amplitude. It was found that the increase of the corrugation amplitude leads to the increase of the damping parameter. By performing the VNA-FMR measurements, Mr. Turčan developed skills in the analysis of very small signals using network analyzers, performed reference sample measurements and calibration measurements, analysis of absorption peaks (automated and manual modes). These results were published by Mr. Turčan in APL with Mr. Turčan acting as the first author. With these achievements, Mr. Turčan successfully accomplished this goal.

Problem solving and dissertation results:

There were two main challenges in the thesis. The first challenge was related to the fabrication of highly curved templates. The decision of Mr. Turčan to use for this purpose FEBID is very important for the success of the thesis. The well documented fabrication parameters are of relevance not only for the next generations of students in the group but also encouraging for the entire community of curvilinear magnetism. In this respect, Mr. Turčan provided a clear validation that FEBID can be used for the fabrication of highly periodic large area curvilinear templates, which can be explored for further research on the geometry induced effects in corrugated thin films. Appealing follow-up studies could include the possibility to write 2D periodic arrays and the use of magnetic thin films with out-of-plane easy axis of magnetization. Another challenge is related to the fabrication of high quality thin films, which allow to study the impact of the geometry induced effects on statics and dynamics of corrugated thin films. The possibility to realize in-plane isotropic FeNi thin films and applied methods to minimize other sources of anisotropy are very important to obtain clean results on the geometry induced effects. Again, these results are encouraging for the experimentalists working in curvilinear magnetism. With these knowledge, it is possible to apply the available theory of curvilinear magnetism to search for the geometry induced chiral effects in these samples.

Importance for practice or development of the discipline:

The remarks on the importance of the results for the development of the curvilinear magnetism are given in the previous section. Furthermore, it is to be expected that these results will stimulate further experimental activities on 3D magnonics. Indeed, to proceed efficiently with 3D magnonic platforms, it is important to understand the behavior of spin waves in corrugated waveguides for the design of prospective 3D magnonic devices. Another important aspect, where I see strong potential of the presented material science platform is the further research on curvilinear spintronics and spinorbitronics. The study of magnetotransport in corrugated stripes would be another impactful research direction. To sum up, the thesis by Mr. Turčan put forth a firm foundation for numerous research directions oriented on the search and use of geometry induced chiral effects in 1D and 2D corrugated samples, study of fundamentals of 3D magnonics and curvilinear spintronics and spinorbitronics.

Formal adjustment of the thesis and language level:

The work is written in a very good English. Didactically, the thesis are also very well structured. The explanation flow and the general narrative are well chosen. It was really a pleasure to read the thesis.

The study is duly completed by a state doctoral examination and the defense of a dissertation, which proves the ability and readiness for independent activity in research. The dissertation includes original and published results.

Questions and comments:

1) Quadratic dependence of the geometry induced anisotropy on the corrugation amplitude is stated (figure 4.13 and corresponding discussion). However, without a detailed quantitative analysis of the data (fit to the data is not shown) it is not clear if the dependence is quadratic for all samples or there is a crossover from the linear to quadratic trend. I recommend to add such an analysis and its discussion.

2) It was demonstrated that the samples with the corrugation amplitude of less than about 8 nm do not have much effect on the dynamic properties of the samples. I would appreciate a discussion on why there is this threshold.

3) Exchange constant: to understand the behavior of a magnetic system, it is important to know all micromagnetic parameters. Mr. Turčan measured the saturation magnetization using VSM and analyzed anisotropy of the samples based on MOKE studies. There is another important micromagnetic parameter, which is the exchange constant. As far as I understood, Mr. Turčan used bulk value for the exchange constant, which is a valid approach for 10 nm thick FeNi films. Still, for completeness, during the defense I recommend to offer a discussion on how the exchange constant can be measured experimentally. Furthermore, when would one expect an onset of finite size effects? It would be insightful to briefly introduce methods for the analysis of the exchange constant for ultrathin films, see for instance [Phys. Rev. Appl. 12, 064038 (2019) and references therein].

4) Curvature effects: considering that the thesis are focused on curvature effects, I find the description of curvature effects rather brief. Limiting the geometry induced effects to the anisotropy only is not complete. Curvature in thin films brings about chiral interaction (linear in curvature; large effect for small curvatures) and anisotropy (quadratic in curvature; small effect for small curvatures) when limiting the discussion to the local interactions like exchange and DMI [Scientific Reports 8, 866 (2018); Phys. Rev. B 94, 144402 (2016)]. The curvature induced chiral effects are not discussed in the thesis. Furthermore, regarding anisotropy: for the case of geometrically curved *ultrathin* films and wires, the magnetostatic interaction can be reduced to local anisotropy only [J. Phys. A: Math. Theor. 50, 385401 (2017); Phys. Rev. Lett. 119, 077203 (2017)]. However, if the thickness of the film is larger than the exchange length, non-local effects can become relevant [Communications Physics 3, 128 (2020)]. For instance, it is predicted that the non-local magnetostatics results in a new type of non-local chiral interaction in curvilinear thin films. I suggest to add more discussion of curvature effects (especially, review local and non-local effects) during the defense.

Conclusion:

In my opinion, the reviewed thesis fulfills all requirements posed on theses aimed for obtaining PhD degree. This thesis is ready to be defended orally, in front of respective committee.

In Dresden, Germany, date 13.06.2022

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Dr. Denys Makarov