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Review of the PhD doctoral dissertation of
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„*Magnetization statics and dynamics in selected ultrathin films and multilayers with Dzyaloshinskii-Moriya interaction*".

PhD thesis of Mr. Anuj Kumar Dhiman were prepared in Department of Physics of Magnetism, Faculty of Physics, University of Bialystok, under supervision of dr hab. Ryszard Gieniusz, prof. UwB and co-supervision of dr Piotr Mazalski. The thesis were prepared in the framework of Polish National Science Center project Beethoven, no UMO-2016/23/G/ST3/04196, under the title "*Domain wall dynamics and magnetic texture behavior in magnetic films with Dzyaloshinskii-Moriya interaction*".

The topic of the thesis is the experimental study of the static and dynamic magnetic properties of ultra-thin layers and multilayers with interfacial Dzyaloshinskii-Moriya interaction (IDMI). Some of the results of the dissertation have been already published in 3 scientific journals, two in J. Magn. Magn. Matter. and in AIP Advances. A. K. Dhiman is the first author in these three papers. The dissertation is written in English, it consists of 6 chapters, abstract in Polish and English, list of abbreviations, symbols and samples, conclusions and the list of the PhD candidate's publications and conference presentations. In total, the thesis counts for 140 pages.

The dissertation is clearly written, well organized and contains interesting experimental results obtained by the PhD student, significantly going beyond the current state of knowledge and advancing the study of the magnetic properties of ultra-thin ferromagnetic metals. Each chapter ends with short summary and bibliographic list. The cited papers have been selected adequately to the discussed topics, and their selection shows a very good knowledge of current literature on the thesis topic.

I start the description of the individual parts of the dissertation with an abstract. It is well written and covers all important parts and results of the dissertation. Chapters 1 to 3 provide nice introduction to the subject of magnetism. The introductory chapters have been written concisely, contain definition of the basic interactions and quantities present in the materials under investigation, and used in the analysis. Chapter 3 provides description of the fabrication and experimental methods used in the PhD research. Especially, this chapter is very well and clearly written. However, the author did not avoid mistakes and ambiguity. In my opinion, the only missing phenomenon that would be useful to describe is the Stoner-Wohlfarth model, which is used several times in the dissertation to explain the experimental results. There are also unclear formulations, like "*Spin and charge together forms the magnetization*" (p. 17), "*In thin films, dipolar interaction plays a key role in anisotropy and it comprises crystalline, …*" (p.18), "*Exchange integral J will*

be trivial for electrons on farther distance". It is not clearly stated, what is a relation between J_{ij} in eq. 2.1.3 and J, just in the next paragraph. Also the meaning of the following statements are unclear: "*the higher order terms are trivial*" on p. 30, "*it causes 'stray field' outside the sample, this stray field results in a demagnetizing field inside the sample*" on p. 31. I think, the statement on p. 34 "***Recently**, magnetic domains in magnetic multilayers have found with hybrid with hybrid structures …*" or "*Bubble domains **are applicable** in magnetic memory …*" are not strictly speaking correct. Are the equations (2.1.17-2.1.18) valid for any ellipsoid sample or only if they are in full saturation? In these and following equations "N_d" is a scalar or tensor? For which type of lattice is the formula for the exchange constant on p. 27 provided? It is not clear, what is the differences between D_{eff} , D and 'd_{ij}' used on p. 29 in the text, equation 2.1.6, and Fig. 2.3, respectively. It is not clear what kind of spin waves are shown in Fig. 2.10, and if they are equivalent? The statement on p. 41 "… *phase of the spins remain **collinear** with magnetic field* ..." is not clear. In Fig. 2.12 the legends are wrongly assigned to the dispersion curves. In Fig. 3.15 the arrow orientation at b_1 and b_2 ports is misleading. Also, there are punctuation errors (e.g., "*major sections**;** (i)* .." on p. 17), misprints, like: double definition of abbreviation 'SW' in successive sentences (p. 18), "*which is symmetric **is*** .." (p. 19), "*walker field*" and '*fermi level*' from small letters. Also double definition of μ_0 on p. 27 is present.

The chapters 4-6 cover the research results performed directly by the candidate. The results are arranged according to the samples under investigation and methods of their deposition. In Chapter 4 the results of measurements of the Co ultrathin layers with different coverings, prepared by sputtering and MBE, are described. It is very well written chapter and presents comprehensive experimental characterization of magnetic properties of Co wedge layer. In Chapter 4.1 the Co of the thickness from 0 to 3.6 nm in the Ir/Co/Pt (Pt/Co/Ir) and Au/Co/Pt (Pt/Co/Au) samples have been studied. Particular interesting are the results relating to IDMI and damping. I rate this research very highly. There are small number of misprints, like missing 'k' in the last term in eq. 4.1.4. It is not clear why different values of M_S of Co in Ir/Co/Pt and Au/Co/Pt based samples was assumed. In my opinion, showing the measured dispersion relation of spin waves will make this chapter even stronger. In Chapter 4.2 the results of the MBE deposited Re/Co/Pt and Pt/Co/Re structures characterization are presented. Here, also the extended experimental results are presented. The chapter is well written and the presented results are novel and interesting. I have only a few comments to this chapter. The definition of the dead layer is not clear, as well as meaning of the negative values of d_0, which are visible in Fig. 4.2.3 c. My attention was drawn to the difference between the dependences of the anisotropy field for $d_{Re} = 0$ in Fig. 4.2.7 in a) and b) (black line). What could be a reason for this?

In Chapter 5.1 there are results obtained for the multilayers based on Co ultrathin films with symmetric and asymmetric composition of the neighboring nonmagnetic metallic materials, Ir and Pt. The results presented here are interesting but their novelty is rather moderate in my opinion. Intriguing are the results shown in Fig. 5.1.5, clearly demonstrating nonreciprocal spin waves in the system. However, it is not clear, why the candidate did not add the plot of the Δf, a standard measure of the nonreciprocity. Is this dependence linear in k for different H field values? Interesting results are presented for symmetric Co multilayers, Pt/Co in Chapter 5.2. Here, the VNA-FMR and BLS measurements of the spin-wave dynamics, not only for Damon-Eshbach (DE) mode but also perpendicular standing spin waves (PSSW) have been analyzed. Interesting, a nonreciprocal properties have been observed for DE mode but not for standing modes. It is not clear, why the author showed the Stokes and anti-Stokes line in Fig. 5.2.8 on the separate plots not on the single one with the positive and negative wave vectors. Has the candidate some guess, why for PSSW the nonreciprocity is negligible?

Chapter 6 is focused on remagnetization studies in ultrathin CoFeB layers. I found the presented results very interesting, going well beyond the state-of-the-art, and pointing out directions for further investigations. In particular, intriguing are observation and analysis of narrow stripe domains, which can be further investigated for application, for isntance in magnonics, as indicated by the candidate.

Overall, the dissertation are well prepared and the presented research is of high quality. However, the author did not avoid editorial errors, in particular unclear rule of using a capitol letters inside the sentence. Also there are number of misprints, some already mentioned, and the other, like missing accent in 'Neel', in the name 'Dzyaloshinkii', on p.55 'van der walls' from small letter. The space after full stop and commas are missed in some cases. It is lack of consistency in using multiplication symbol, for the multiplication of scalars in some cases '.' in other '×' is used. The SI and cgs units are mixed in the thesis, e.g., eq. 2.3.10 and 2.3.11, which introduce some inconsistency into the thesis. In bibliography the are misprints, e.g., p. 38 in [38] is 'barman', in [54] is twice "Nat. Phys.", in [56] missing come after first name. In p. 44-45 in some items the first letters in the titles are from capital in others with small letters. In Ref. [55] the is no information about the publisher.

Summarizing, I state that Mr. Anuj Kumar Dhiman obtained a number of interesting research results, some of which were published in good scientific journals, and they described in an interesting way in the doctoral dissertation. I am convinced that the presented research constitutes a significant contribution to the development of the physics of magnetism, in particular the currently rapidly developing area of the physics of ultrathin ferromagnetic films with interfacial induced DMI. All these achievements of Mr. Anuj Kumar Dhiman clearly indicate that he is a mature scientist with good research achievements in experimental physics of magnetism.

Summing up, I believe that the presented dissertation meets all the requirements of the Law on Higher Education and Science of July 20, 2018 for doctoral dissertations, and I am asking for admission of Mr. Anuj Kumar Dhiman to the next stages of the doctoral dissertation.

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