Dr. hab. Aleksandra Trzaskowska, prof. UAM
[Ph.D., postdoctoral degree holder, professor of the Adam Mickiewicz University]
Institute of Spintronics and Quantum Information
Faculty of Physics
Adam Mickiewicz University in Poznań

Poznań, 11.05.2023

A review of the doctoral dissertation of Sukanta Kumar Jena, M.Sc., entitled: "Magnetic properties of asymmetric layered heavy metal/ferromagnet systems".

The doctoral dissertation presented for review, written by Sukanta Kumar Jena, M.Sc., was carried out at the Institute of Physics of the Polish Academy of Sciences in Warsaw under the direction of Prof. dr hab. Andrzej Wawro *[professor, Ph.D., postdoctoral degree holder]* acting as supervisor, and Dr. Ewelina Milińska *[Ph.D.]*, acting as associate supervisor. Research for the doctoral dissertation was co-financed from the funds of the project funded by the Foundation for Polish Science within the framework of the European Regional Development Fund program (REINTEGRATION 2017 OPIE 14-20) and projects of the National Science Centre (2016/23/G/ST3/04196 and 2020/37/B/ST5/02299).

The work is experimental and devoted to asymmetric ultra-thin W/Co/Pt multiple layers with magnetization perpendicular to their surface with different numbers of repetitions of the basic W/Co/Pt trilayer. These size-reduced multilayer systems are characterized by strong perpendicular magnetic anisotropy (PMA). In addition, the different proximity of the ferromagnetic layer (Co) with the layers of heavy metals (in this dissertation, these are W and Pt) results in the occurrence of the Dzyaloshinskii-Moriya interaction (DMI). The studied multilayer structures were produced by molecular beam epitaxy (MBE), which allowed to obtain samples with a higher quality of the crystal structure forming individual layers in comparison to the commonly used sputtering method. The results shown in the presented doctoral dissertation are interesting in the context of practical applications (as magnonic crystals or potential carriers of magnetic recording); at the same time, they are fundamental research.

The dissertation was prepared in English in the classic form, covering 114 pages. The dissertation consists of six chapters, and each of them is provided with a table of contents and separate literature, an abstract in Polish and English, a list of symbols and abbreviations used, and very extensive acknowledgments. In addition, there is a list of papers co-authored by the Ph.D. candidate (2 papers), a list of conferences and seminars where the Ph.D. candidate presented the results of his research, scientific trips and internships, and a list of grants. The doctoral dissertation ends with a short summary.

The first chapter of the doctoral dissertation, which is an introduction, outlines the cognitive goal set by the Ph.D. candidate and briefly discusses the content of the subsequent chapters of the doctoral dissertation.

The goal of the dissertation was to study and determine the effect of the sequence, layer thickness, and the number of repetitions of the W/Co/Pt triple-layer system on the magnetic states and domain structure of the studied layered system. In addition, the values of the Dzyaloshinsky-Moriya interaction (DMI) were determined.

In the first chapter of the doctoral dissertation, the author defines his personal contribution relating to the scope of the work. The Ph.D. candidate designed most of the samples himself, he participated in their preparation as well as their structural and magnetic characterization. He independently measured the domain structure and carried out calculations of the DMI coefficient based on the model of the magnetic effective medium. In addition, in relation to the paper entitled "Interfacial Dzyaloshinskii-Moriya interaction in epitaxial W/Co/Pt multilayers" (*Nano scale* ***13*** *(2021) 7685-7693)*, the Ph.D. candidate independently prepared a preliminary version of the manuscript and actively participated in editing its final version. From an editorial point of view, references 2,3,5,6 in this chapter are not complete.

The second chapter is an introduction to the subject of magnetism and contains basic concepts and definitions of quantities used in the analysis of experimental results. This chapter provides a very concise and often basic overview of each topic. The Ph.D. candidate did not avoid editorial errors, in particular the inconsistency in the symbols used, in particular: in equation 2.1 E_Z was defined as Zeeman energy, while in the list containing the most frequently used symbols it is E_{Zee}; in equation 2.2, what is H?; in equation 2.3, μ_0 and d are not defined. Equation 2.4: what do H_{IEC} and d mean (although Equation 2.4 is described in Chapter 5), and in equations 2.5 and 2.6, α_i, ϕ?. The most commonly used symbol θ in many equations is defined in different ways, and the opposite situation applies to the thickness of the layers (denoted as d or t) and the width of the domain walls. From the editorial point of view, the size of some drawings is incomparably large to other drawings, which in turn means that the caption for a given drawing is often on the next page, which is also present in the entire doctoral dissertation. In terms of content, the reader may feel a certain insufficiency in the description of, for example, domains and domain walls, or the impact of DMI. The presented doctoral dissertation refers to the above-mentioned issues, which is why I believe that in the theoretical part, they should be more developed. The last of the subchapters in this part of the dissertation is admittedly treated briefly, and when presenting Figure 2.9, one should at least give the basic relations corresponding to the interaction of light with spin waves, the more so that the Brillouin light scattering method allowed to determine the DMI parameter.

The third chapter presents the research methodology used in the doctoral dissertation. The Ph.D. candidate discussed the method of producing the multilayer systems (molecular beam epitaxy, MBE) and the research methods used: SQUID magnetometry, polar magneto-optic Kerr effect (PMOKE), magnetic force microscopy (MFM) and Brillouin light scattering (BLS) spectroscopy. The experimental methods used by the Ph.D. candidate are described in a rather general way. In my opinion, the description of the equipment should be clarified in many places. The Ph.D. candidate does not provide technical details of individual methods, e.g. at what laser wavelength does the Brilouin spectrometer work, and what type of spectrometer is it? Which SQUID magnetometer and which AFM microscope are we dealing with? What is the resolution of the AFM and MFM microscopes? Also, the equation on page 56 is not numbered. This equation refers to the calculation of the Dzyaloshinskii-Moriya interaction constant, but it is not specified how the value of the wave vector *[k-vector]* is calculated. As a standard, in Brillouin spectroscopy, determining the DMI constant should take into account the two directions of the magnetic field (+H and -H) in the DE (Damon-Eshbach) configuration. Do the presented results take into account this configuration of the magnetic fields? Chapter 3.9 describes the hysteresis loop without any reference to the research equipment – in its current form, this chapter should rather be included in the theoretical part, not in the description of the equipment. However, I must point out that reading the description of the equipment clearly shows the Ph.D. candidate's extensive knowledge of the MBE method and its technical aspects.

Chapters 4-6 contain the results of experimental research, which are the core of the submitted doctoral dissertation. Chapter 4 presents the results of research on structures with a single layer of cobalt. The aforementioned chapter in the first part describes the state of knowledge about Mo/Co/Au samples. Such structures are apparently similar to W/Co/Pt structures (Mo and W are characterized by the same crystal structure and similar lattice parameters, while Au and Pt belong to the group of heavy metals and are neighbors in the periodic table). Despite the apparent similarity of the Mo/Co/Au and W/Co/Pt systems, the Ph.D. candidate showed that the W/Co/Pt system he studied is characterized by a different range of Co (d_{Co}) layer thicknesses, in which PMA appears. In addition, the Ph.D. candidate studied the effect of the W layer thickness (d_W) on the occurrence of PMA in the Pt/W(dW)/Co(dCo)/Pt system. A study of the magnetic states (PMOKE) performed by the Ph.D. candidate for a sample with variable W (0-100 Å) and Co (0-30 Å) thicknesses show areas with different properties: from non-magnetic to super-paramagnetic, ferromagnetic with PMA and ferromagnetic with magnetization lying in the plane of the layer. In addition, an interesting result is the demonstration of the existence of spin reorientation transition (SRT), which can be caused by both a change in the thickness of the cobalt layer and a change in the thickness of the tungsten layer. For the selected configuration of the system, the existence of bubble domains was also demonstrated, which was additionally confirmed by the value of the DMI. The DMI value obtained in the experiment was referred to W(l)/Co(18)/Pt(5) samples based on work [20]. I would like to mention that the values obtained by the Ph.D. candidate and those from individual papers by other authors are effective values (D_{eff}), therefore it would be interesting to take into account the thickness of the tested magnetic layers, i.e. to compare the surface DMI (D_s), and not the effective DMI (D_{eff}).
Roughness – unevenness of the surface of the W/Pt samples was determined on the basis of the AFM study of the surface topography (Figure 4.5a) at the level of 2 Å. Making such a conclusion is possible based on the height profile of the tested sample – what does this profile look like? The content of the discussed chapter largely coincides with the paper of: Z. Kurant, S.K. Jena, R. Gieniusz, U. Guzowska, M. Kisielewski, P. Mazalski, I. Sveklo, A. Pietruczik, A. Wawro, and A. Maziewski; *JMMM **558** (2022) 169485*, of which the Ph.D. candidate is a co-author. The Ph.D. candidate's contribution to this paper is defined as "Investigator" (as the Ph.D. candidate himself writes about in his doctoral dissertation), I believe that this term should be clarified.
From the editorial point of view, in this chapter, references 3-5, 7, 9-12, 14, 16, and 17 are not complete; references 20 and 21 are the same publication, moreover, the reference style of this chapter is different from the other chapters in the doctoral dissertation.

Interesting research results, described in an interesting way, are included in Chapter 5 of the doctoral dissertation. The conducted research concerns multilayers where the number of repetitions is in the range of 2-7. For the $Pt/[W/Co/Pt(d_{Pt})/W(d_W)/Co/Pt]_2$ system, the Ph.D. candidate showed the occurrence of antiferromagnetic coupling with a maximum for Pt and W layers with a thickness of 7 Å and estimated its magnitude based on the length of the visible plateau in magnetic hysteresis loops. The occurrence of the aforementioned coupling depends on the thickness of the Pt and W layers. The thickness of the mentioned layers also has a significant impact on the relationship between the exchange coupling and the magnetostatic interaction for systems where the number of repetitions of the base trilayer was 6 and 7. The Ph.D. candidate also showed the existence of a stable labyrinth domain structure in the remanent state for the tested multilayers in a situation where the magnetostatic interaction prevails.

The last, sixth chapter of the doctoral dissertation presents the results obtained for systems with the number of repetitions of 10 and 20. This chapter is entirely based on the paper of: S.K. Jena, R. Islam, E. Milińska, M.M. Jakubowski, R. Minikayev, S. Lewińska, A. Lynnyk, A. Pietruczik, P. Aleszkiewicz, C. Autieri, A. Wawro; *Nanoscale **13** (2021) 7685*, in which the Ph.D. candidate is the first author. In my opinion, this is the best chapter in the dissertation presented for evaluation. In this chapter, the Ph.D. candidate presented in detail the structural characteristics of the studied systems. The samples were very well characterized in magnetic terms (Table on page 98). It was shown that the studied systems can have a labyrinth and strip domain structure – for which the period was determined. The size of the domain structure made it possible to determine the value of the DMI coefficient of the studied multilayer systems using the model of the magnetic effective medium. The value of the DMI coefficient is relatively high (2mJ/m2), which has been associated with the high quality of the samples in terms of their crystalline structure. The experimentally obtained DMI value was confirmed numerically, i.a. using micromagnetic simulations. The question arises whether the higher value of the DMI coefficient occurs only in the W/Co/Pt triple-layers or is it also visible in other systems of this type studied by the Ph.D. candidate? Furthermore, I would like to mention that in this chapter, in the discussion, the Ph.D. candidate writes about the next chapter discussing the results obtained for the Re/Co/Pt material, which is not included in the doctoral dissertation. From an editorial point of view, the last of the subchapters is incorrectly numbered, while references 3, 5, 7, 8, and 22 are not complete.

I believe that the main achievement of Sukanta Kumar Jena, M.Sc., in the presented doctoral dissertation is the demonstration of the possibility of intentionally tuning the PMA, DMI, IEC, and magnetostatic interactions in asymmetric layer structures of heavy metals and ferromagnets. Thus, the Ph.D. candidate achieved his goal, i.e. he showed how the thickness of the component layer and the number of repetitions of the basic triple-layer stack (W/Co/Pt) affect the discussed magnetic properties.

In conclusion, I find that Sukanta Kumar Jena, M.Sc., obtained several interesting results that were published in two journals with an impact factor of 3.097 *(JMMM)* and 8.307 *(Nanoscale)*. I am convinced that the presented research results are a significant contribution to the development of the physics of magnetism and significantly expand the state of knowledge regarding the magnetic properties of thin films in heavy metal/ferromagnetic systems.

The doctoral dissertation of Sukanta Kumar Jena, M.Sc., entitled: "Magnetic properties of asymmetric layered heavy metal/ferromagnet systems" performed in the field of exact and natural sciences and the discipline of physical sciences, meets the formal requirements of the Act of 20 July 2018 – The Law on Higher Education and Science. Taking into account both the substantive and formal context, I request that Sukanta Kumar Jena, M.Sc., be admitted to the further stages of the proceedings for awarding the degree of Doctor of Physical Sciences.

[legible signature] ***Aleksandra Trzaskowska***

/signed by: Dr. hab. Aleksandra Trzaskowska, prof. UAM
[Ph.D., postdoctoral degree holder, professor of the Adam Mickiewicz University]/