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A review

of the doctoral dissertation of Sukanta Kumar Jena, M.Sc.

Magnetic properties of asymmetric layered heavy metal/ferromagnet systems

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The review of the doctoral dissertation with the above-mentioned title in the field of exact and natural sciences in the discipline of physical sciences was developed based on the resolution of the Scientific Council of the Institute of Physics of the Polish Academy of Sciences of 30.03.2023.

Selection of the topic of the dissertation and its goals

The doctoral dissertation of Sukanta Kumar Jena, M.Sc., deals with experimental studies of thin-film hybrid heavy metal (HM) and ferromagnetic (FM) systems. This issue is an important issue of spin electronics due to the possibility of developing new, energy-saving technologies for storing and processing information based on the lossless spin current, which is why this topic is part of the so-called green IT trend.

Heavy metals exhibiting strong spin-orbital coupling, such as Pt and W, are mainly studied in two directions: in terms of the efficiency of spin current generation as a result of the Spin Hall Effect and their use as a spin current source, as well as in terms of the asymmetric magnetic Dzyaloshinskii-Moriya interaction (DM1) characterized by a skyrmion spin texture. The first direction requires the production of nano-size spintronic elements and is application-oriented, for example, on the design and study of SOT-MRAM (Spin-Orbit Torque Magnetoresistive Random Access Memory), while the second, at the present stage, is basic research on the magnetic spin texture as a result of DMI-type exchange interactions and magnetic anisotropy.

The doctoral dissertation of Sukanta Kumar Jena, M.Sc., discusses the results of asymmetric W/Co/Pt multilayers deposited with the MBE (Molecular Beam Epitaxy) method. The asymmetric surrounding of the ferromagnetic layer (Co) with layers of heavy metals (W and Pt), characterized by strong spin-orbital coupling, with opposite signs of interaction, induces the DMI, which significantly modifies the spin structure of the magnetic layer systems, leading to the formation of skyrmion spin spirals.

In contrast to the magnetron sputtering systems extensively discussed in the literature, the MBE technique provides a well-defined crystal structure of the component layers and high-quality interfaces that are crucial for the observed phenomena. It is precisely this experimentally set aim of research to demonstrate the importance of interface inputs to the interaction of DMI that is the primary goal of the research presented in the doctoral dissertation of Sukanta Kumar Jena, M.Sc.

The content of the dissertation and general remarks

The presented doctoral dissertation has 113 pages, it is written in English, and it has been divided into 6 basic chapters preceded by abstracts in Polish and English, a list of the most frequently used symbols and abbreviations, and the scientific achievements of the Ph.D. candidate. Chapter 1 *Introduction* introduces the content of the doctoral dissertation, and the Ph.D. candidate justifies the scientific novelties of the conducted research in relation to the current state of knowledge, as well as defines the basic goals he has set himself. Chapter 2 *Theoretical review* is short, and it contains very basic, general, well-known, textbook knowledge of thin-film magnetism. Subchapter 2.7 *Dzyaloshinskii-Moriya Interaction (DMI)* is disappointing because the author does not discuss the state of the art of published theoretical models of iDMI, in reference to his own results described in chapter 6 *Interfacial Dzyaloshinskii-Moriya interaction in the epitaxial W/Co/Pt.*

Chapter 3 *Experimental techniques* is well-edited and discusses the MBE layering technologies and the structural and magnetic characterization methods used. To prove and achieve the assumed goals, the Ph.D. candidate correctly selected the research methods, demonstrating great ease and efficiency in using the techniques of application and characterization of the samples produced. The Ph.D. candidate used the RHEED (*3.4. Reflection High Energy Electron Diffraction),* ex-situ X-ray diffraction (chapter *3.5. XRD)* and low-angle XRR (3.5. *X-Ray Reflectivity)* methods to control epitaxial growth during deposition*.* Magnetic properties, hysteresis loops M(H) were measured locally using the magneto-optical Kerr effect *(chapter 3.6. MOKE),* saturation magnetization was assessed from measurements *(3.8. SQUID),* changes in the domain structure in the remanence state (due to the need to use a high-resolution technique of less than 1 µm) was examined with a magnetic force microscope (*3.7. MFM),* magnetization dynamics and DMI interaction strength were studied by BLS spectroscopy *(3.10:- Brillouin light scattering spectroscopy).* Subchapter 3.1, *Molecular Beam Epitaxy technique,* also the chapters on the structural characteristics of the produced samples, lack the discussion about the important role of the *seed* layer*,* initiating the growth of the complete sample, and why he used the 10 nm or 40 nm Pt layer, what effect did it have on monocrystalline properties and quality of interfaces?

In the following chapters, from 4 to 6, the Ph.D. candidate analyzes the results of research that were previously published in two papers:

- Sukanta Kumar Jena et al. *Interfacial Dzyaloshinskii-Moriya interaction in epitaxial W/Co/Pt multilayers* Nanoscale 13 (16), 7685-7693, 2021
- Zbigniew Kurant, Sukanta Kumar Jena et al. *Magnetic ordering in epitaxial ultrathin Pt/W/Co/Pt layers* Journal of Magnetism and Magnetic Materials 558,169485, 2022.

According to the Ph.D. candidate's statement in both publications, he was the primary experimenter in the field of applying samples, carrying out most of the measurements. On the other hand, he contributed the greatest commitment (according to his statement) to the publication in Nanoscale (2021) that relates to the basic thesis of the dissertation – the interface interaction of iDMI in multilayer systems $[W/Co/Pt]_N$ (N=10 and 20).

In order to achieve the assumed goal – research on the DMI interaction, which induces a topologically stable skyrmion structure in epitaxial W/Co/Pt structures, the Ph.D. candidate fabricated and systematically studied various combinations of HM/FM layer combinations guaranteeing perpendicular magnetic anisotropy (PMA) and a high value of the effective DMI constant (D_{eff}>2mJ/m^2).

In Chapter 4 *Structural and magnetic properties of single and multilayers W/Co/Pt heterostructures* Sukanta Kumar Jena, M.Sc., starts the research with the quality control of the RHEED epitaxial growth of W and Co layers with variable thickness deposited on an Al_2O_3 substrate (0001/buffer Pt 40 nm. The high-resolution cross section obtained by electron microscopy *(HRTEM cross-section,* Fig.4.5) shows very good growth of the individual layers of Pt, W, and Co, which confirms the high quality of the samples produced. Then, he determines, by varying the thickness of d_W = 0 ÷ 10 nm and d_{Co} = 0.3 ÷ 3 nm, the critical thicknesses for W and Co for the transition from in-plane anisotropy to perpendicular anisotropy (so-called critical thickness of *Spin Reorietation Transition,* SRT) (Fig.4.8 and Fig.3 JMMM) on Pt(40)/W(d_W)/Co(d_{Co})/Pt(3) samples. Using the Pt/W(d_W)/Co(1.8)/Pt system as an example, he investigates the spin polarization state of the W/Co and Co/Pt interfaces *(proximity effect).* Based on BLS measurements on the Pt/W(2.4)/Co(0.6)/Pt sample, he determines iDMI=1.12mJ/m^2, and obtains a value that is much higher than for the same layered systems applied by cathodic sputtering (D_{eff}=0.2 mJ/m^2). On the same sample, going from a labyrinthine domain structure in the remanence state, he induces a bubble-like DS with a magnetic field (=-0.36 mT) (Fig. 4.10 d, Fig. 5d JMMM). The research performed was published in a paper in JMMM(2022).

Data from the tests of the W/Co/Pt system regarding the thickness ranges of the layers providing PMA, iDMI, and bubble-like DS are the starting point for the Ph.D. candidate to design the Interlayer Exchange Coupling (*IEC*) systems described in Chapter 5 *W/Co/Pt structures with moderate repetition number.* The purpose of his research was to test whether, in addition to the DMI, other effects such as just IEC coupling and the magnetostatic dipole interaction induced by the domain structure enhance the topological stability of the skyrmion structure. The Ph.D. candidate produces a matrix of cells on the Al_20_3(0001)/Pt(40)/W(l)/Co(l)/ Pt(dPt)/W(dW)/Co(l)/Pt(3) system, which he then examines as a function of changes in the thickness of the W and Pt layers. No compression is observed when the spacer is of the same type of W or Pt material. In the case of a spacer composed of a double Pt/W layer, he obtains antiferromagnetic coupling in the range from 1.4 nm to 2.4 nm for the case of equal thicknesses of Pt and W (d_{Pt} = d_W). On the other hand, antiferromagnetic coupling decreases with increasing d_{Pt} + d_W with a tendency to change to ferromagnetic. The Ph.D. candidate shows M(H) loops outside the diagonal of the matrix (d_{Pt} = d_W), which are both ferromagnetic and antiferromagnetic couplings, and he does not explain what mechanism and what nature of coupling we are dealing with.

Another interesting result described by the Ph.D. candidate in subchapter 5.2. *Couplings in W/Co/Pt multilayers* is the creation of an artificial antiferromagnet structure *(Synthetic Antiferromagnet, SAF)* [Co(l)/Pt(dPt)/W(dW)/Co(l)]n/Pt(3) with two thicknesses of the Pt/W spacer with dW = dPt equal to 0.5 nm and 1 nm and the number of repetitions n=6 and 7. For the spacer n=6, he obtained, as expected, a compensated SAF, and uncompensated SAF for n=7. Both systems exhibit multiple switching during remagnetization with a perpendicular field. This effect of multi-state magnetization switching, induced by spin-orbit interaction, antiferromagnetic interlayer coupling, in the presence of perpendicular magnetic anisotropy, is, in my opinion, potentially of great practical importance. The research results described in Chapter 5 have not been published.

Sukanta Kumar Jena, M.Sc., obtained significant amplification of the dipole magnetostatic interaction due to the strong labyrinth domain structure (Fig. 5.8) for the systems $[W(l)/Co(l)/Pt(l)]_n$ with n=6 and 7. The Ph.D. candidate developed this problem by studying the systems $[W(l)/Co(0.6)/Pt(l]_n$ with n=10 and 20; the results were described in Chapter 6 *Interfacial Dzyaloshinskii-Moriya interaction in the epitaxial W/Co/Pt multilayers* and published under the same title in Nanoscale (2021).

Based on the research described in the article and in Chapter 6 of the dissertation, the following most important conclusions from iDMI studies in epitaxial W/Co/Pt layers can be formulated:

- multilayer systems [W(l)/Co(0.6)/Pt(l]n of the superlattice type produced by the MBE method show a very good crystalline quality of the interfaces (no mixing) and a highly textured structure of the layers, in contrast to polycrystalline, poorly textured similar systems commonly produced by the magnetron deposition technique,
- iDMI interaction in such asymmetric systems induces the formation of skyrmion spin structures stabilizing magnetization configurations with non-trivial topology,
- very high values of the D_{eff} coefficient =2.64 mJ/m^2 and the surface DMI parameter D_s = 1.83 pJ/m (significantly exceeding the values obtained for sputtered systems of 0.2 to 1.5 mJ/m^2) determined from the analysis of the stripe domain structure, using the effective anisotropy method, for the number of repetitions n=10,
- the results of the DMI constants obtained in the experiment correlate very well with the results obtained from micromagnetic modeling and calculations of the density functional theory (DFT). Theoretical modeling, based on data from the experiment, was performed by the co-authors of the publication: Ewa Milińska micromagnetic calculations, Rajibul Islam and Carmine Autieri DFT calculations.

Sukanta Kumar Jena, M.Sc., concludes his doctoral dissertation with an edited general summary. The content of the dissertation is clear, and modeled on foreign doctoral dissertations; the chapters are arranged logically, from the introduction to the subject of the researched issue, through the description of research methods, to the research results and the final conclusion. The graphic form is very neat. I did not notice any major errors or mistakes, only minor editorial errors, such as:

- in the title of Chapter 4 it stands: *Structural and magnetic properties of single and multilayers W/Co/Pt heterostructures* but it should be "… *of single Co...*"
- p. 88, bottom reference to "...figure 4.17 (a)." which is not there, probably should have been "figure 5.6"?
- p. 107, the Ph.D. candidate mentions results for the Re/Co/Pt system, but I did not find such throughout the dissertation.

Finally, it is worth mentioning the potential applications of HM/FM systems, which mainly focus on the design and manufacture of current-controlled spintronic devices, in which magnetization switching is carried out by the *spin orbit torque (SOT)* effect.

These solutions, as I mentioned earlier, are primarily used in SOT-MRAMs, in which active layers are applied to a highly resistive buffer layer (e.g. Ta). Due to the required bulk industrial production, the use of oxidized silicon substrates *(Si/SiO_2 wafer),* and compatibility with CMOS technology, a fast deposition method is necessary, which is met by the magnetron sputtering method. The MBE method presented in the dissertation consists in growing (very slow deposition) practically monocrystalline layers, which is why this technology requires very thick seed-buffer layers, in this case, a Pt layer (10 or 40 nm) was used which causes the effect of current shunt effect, which does not flow through magnetically active layers, which results in no interface spin accumulation at the HM/FM interface, and consequently, the SOT switching effect does not work. I would like to know from the Ph.D. candidate what are the possibilities of making a current-switched SOT element using the MBE method, what should be its layer structure?

Evaluation of the dissertation and justification of the award

In conclusion, I state that the doctoral dissertation of Sukanta Kumar Jena, M.Sc., entitled *Magnetic properties of asymmetric layered heavy metal/ferromagnet systems* contains **new very interesting and original results,** partly published in highly indexed journals. The Ph.D. candidate produced and comprehensively studied asymmetric W/Co/Pt structures based on his own experiments and analyses, obtaining much higher DMI values compared to those previously published. Using the original domain model (K_{eff}) he determined the DMI constant of the surface interaction in periodic multilayer systems, which I consider a very original result.

The Ph.D. candidate showed general knowledge of magnetism, and mastered the method of epitaxial deposition of thin layers and their magnetic and structural characterization, thus demonstrating the ability to independently conduct scientific research.

Taking into account the very **innovative and original research results,** their thorough and critical elaboration in the form of a doctoral dissertation and publication achievements, I hereby apply for the distinction of the doctoral dissertation of Sukanta Kumar Jena, M.Sc., entitled *Magnetic properties of asymmetric layered heavy metal/ferromagnet systems.*

Final conclusion

Based on the substantive assessment of the doctoral dissertation, I state that it meets the requirements for doctoral dissertations under the applicable regulations. Therefore, taking into account the publications of Sukanta Kumar Jena, M.Sc., and a very high scientific evaluation result of his doctoral dissertation, I believe that according to the Act of 14 March 2003 (Journal of Laws No. 65, item 595, as amended) on Academic Degrees and Academic Titles, and Academic Degrees in Art, Sukanta Kumar Jena, M.Sc., meets the requirements for candidates for the scientific degree of doctor of physical sciences in the field of exact and natural sciences in the discipline of physical sciences, I apply for admission to the public defense of the presented dissertation and I apply for its distinction.

[podpis nieczytelny]