Review Report on PhD Thesis

Faculty: **Central European Institute of Technology**
Brno University of Technology in Brno

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Student: **Meena Dhankhar**

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

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

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

Reviewer: **Dr. Aleš Hrabec**

PhD thesis title: **Magnetic vortex based memory device**

Topicality of doctoral thesis:

The topic of this PhD work concerns the fabrication, characterization and control of magnetic state of magnetic vortices. Magnetic vortices, in comparison to the conventional binary memories, offer data storage in 4 states: 2 in their circularity and 2 in their polarity. Their research has been pursued over the last decade by many laboratories world-wide, including the group at CEITEC in Brno. The research encompasses, for example, the control of their magnetic state, the use of vortex oscillators or their synchronization, which has been implemented in novel computation schemes. The topic of the doctoral work, where it's proposed how to electrically independently control the vortex polarity and circularity, is certainly timely and of high technological interest.

Meeting the goals set:

The primary goal of the thesis, i.e. full electrical control of the individual magnetic states and their read-out, has been achieved. I suppose, from academic point of view, one of the goals should also be submission of a first-author paper, which is currently lacking. However, based on the interesting results summarized in this manuscript, I believe that this can be achieved within reasonable time, as also promised in the 'Own Publications' section of the thesis.

Problem solving and dissertation results:

The control and read-out of the magnetic vortices require a good knowledge of the underlying physics of their formation and of the techniques necessary for their characterization. In the course of this project, a significant number of techniques was used, including magnetic force microscopy, transmission x-ray microscopy, Kerr microscopy and high-frequency electric measurements. A non-negligible time has also been spent in the cleanroom optimizing the fabrication processes tailored to all various measurement techniques. The fact that all these processes were successfully implemented was demonstrated by the achieved initial goals. The problems were unravelled despite a few intermediate 'failures', which were solved by further optimization of the used disk geometries or the used magnetic films. The final demonstration of the electric writing uses a smart sequence of electric pulses, where the pulse duration and amplitude set whether the circularity or the vortex polarity is addressed.

Importance for practice or development of the discipline:

As already said in the first part of my report, the importance of this work is driven by the technological interest since the proposed magnetic vortex memories can carry 4 data bits instead of the conventional 2. To make this memory attractive for applications, the vortex polarity and circularity can be deterministically controlled by electric pulses and also read electrically using RF electric current. Moreover, the writing is done in sub-ns regime, which is of uttermost importance for high-frequency operation of such memories.

Formal adjustment of the thesis and language level:

I have read the thesis and I have sent the list of corrections directly to the PhD candidate. I found the thesis very informative covering all the topics necessary to grasp the most important 'Experiments and Discussion' chapter. I think that there is still space to make it more accessible by improving some of the figures and their captions and by linking the final chapter to the introduction. Nevertheless, this can be easily fixed and once it is done so, the thesis is suitable to complete the PhD degree which is ought to be defended in from of the committee.

Questions and comments:

I have a number of questions:

- It has been shown that an underlying out-of-plane magnetized layer can be used to define the preferred vortex polarity. However, the mechanism of the coupling is not mentioned but I understand that this is done via dipolar forces. Can it be estimated how much field is necessary for the successful polarity definition? You have optimized the Co multilayer but the details (e.g. number of Co layers) are not enclosed. I guess that this can be done via micromagnetic simulations or by using an external out-of-plane field substituting the dipolar field. Can this be realized by using a more powerful RKKY coupling between the Py and the out-of-plane layer?
- Section 5.4 is entitled as 'All electric control (switching and readout) of vortex states'. However, to read the polarity and circularity, one still needs the in-plane magnetic field to displace the vortex core from the center. Do you have a vision how this can be eliminated in order to have the fully-electric read-out? Can magnetic tunnel junctions be used to read all 4 magnetic states?

- I find the results shown in Fig. 5.23 very interesting but the deeper discussion is somewhat missing. Can you explain why the success ratio drops down below 100% for higher pulse amplitudes? Perhaps this 'tunability' can be used in unique probabilistic computing schemes (see W. Borders, Nature 2019).
- I think that the sketch displayed in Fig. 5.1(b) is not correct. Can you please show how the magnetic configuration looks like in a disc with a FIBed trench and how does the corresponding stray field look like? Can you comment why there is practically no contrast arising at the vortex core in MFM images in Fig. 5.2.

Conclusion:

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

In Villigen, 12.2.2021

Dr. Aleš Hrabec