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Report on thesis “Quench Switching of Antiferromagnetic CuMnAs” by Zdeněk Kašpar submitted to Charles University, Faculty of Mathematics and Physics

The doctoral thesis of Zdeněk Kašpar presents a detailed study of antiferromagnetic (AF) domain fragmentation using electrical pulses in epitaxial CuMnAs thin-film devices. The nano-fragmentation causes significant changes in the resistivity of the presented devices, which can be controlled using highly reproducible approaches. The topic is highly relevant and timely, addressing current challenges to control and readout antiferromagnetic domain configurations. Electrical transport for both writing and read-out of specific states is also highly compatible with existing memory and computation technologies.

The thesis is structured into six chapters. Chapter 1 gives an introduction to AF spintronics, with a particular focus on the current-induced switching effects in CuMnAs. The phenomenon of AF domain fragmentation is introduced and described mainly in the context of parallel studies focusing on imaging of the resulting AF configuration. Chapters 2 through 6 represent the central part of the thesis.

Specifically, chapter 2 demonstrates the phenomenon of quench switching, showing a dominating resistivity increase upon electrical pulsing, followed by a gradual relaxation. The relaxation is modeled by a multicomponent stretched exponential function, identifying up to four components with significantly different amplitudes and relaxation times, depending on the pulse amplitude and working temperature. Importantly, reversibility of the process and the characteristic time of the thermally activated relaxation indicate the magnetic origin of the studied effect.

Chapter 3 describes different device geometries, introducing Wheatstone-bridge devices that allow convenient comparison of the resistivity increase using perpendicular pulses at different experimental conditions. Further, the importance of heating close to the Néel temperature of the material for maximum switching efficiency is highlighted.

Chapter 4 studies pulse length, frequency, and amplitude dependence in detail, finding limits of the process, such as the breakdown voltage, among others. A unique erasing process, based on sending a weaker pulse shortly after the original one, is found and optimized.

Chapter 5 deals with the quench switching dependence on the substrate material, showing the highest switching amplitude can be reached in homogeneous high crystal quality films. Furthermore, the thickness dependence of the switching amplitude suggests a bulk origin of the effect.

Finally, Chapter 6 describes the methods for growth of CuMnAs thin films, fabrication of devices, and electrical transport measurements.

Mr. Kašpar approached the subject encompassing a broad range of activities, starting from diligent optimization of CuMnAs growth on different substrates, fabrication of devices, through electrical transport measurements that represent the major contribution in the presented thesis, modeling the electrical transport and participating in collaborative projects aimed at ultrafast optical excitation of the CuMnAs devices and imaging of the AF domain structures using NV center magnetometry, XMLD-PEEM, and TEM.

The results of experiments are meticulously discussed, and the findings of each section are clearly and concisely summarized. This step-by-step builds a consistent picture of the phenomenon throughout the manuscript. The thesis presumably focuses on the original work of the author, which gives a rather good overview for the assessment of the author’s contribution. However, especially in the introduction and discussion parts, it is missing some of the relevant contexts that is highly important for the discussion of the mechanism of the switching effect. In this sense, the analysis and subsequent discussion do not go far beyond the presented data. I would expect this aspect elaborated on a significantly higher level.

The formal presentation of the thesis is very good. More care should be given to proper usage of articles in the English text, which is mainly an issue for Chapters 1 and 6, but overall this is not a severe problem. I remind the author to explain all the acronyms and abbreviations used.

In summary, the thesis presents an impressive amount of original findings related to the newly discovered phenomenon of antiferromagnetic domain fragmentation using electrical pulses. A large part of the results has already been published in a number of high-impact papers, attracting significant interest in the magnetism community. For all these reasons, I recommend the committee to accept Mr. Kašpar's thesis for obtaining the Ph.D. degree.

Brno, March 15, 2021 Vojtěch Uhlíř

Questions

Following Fig. 1.8, may the relation of **m** and **p** vectors and orientation of the torques in c)-e) be clarified in more detail?

On p. 24, could the decrease of the signal in NV center magnetometry be explained by a corrugated domain boundary, not necessarily new nano-domains forming?

How was the CuMnAs device optimized in order to allow higher current density pulses? What was exactly the issue?

What is the orientation of the AF easy axis in CuMnAs? Is it possible to orient the Néel vector along arbitrary directions using, e.g., Néel spin-orbit torques?

Is a similar relaxation proces as presented in the thesis observed also for states written using spin-orbit torques?

There are published works on other materials like Mn_2Au (ref. 72, 73) and MnN (ref. 77) describing similar relaxation effects. What are the material parameters influencing the switching efficiency and retention of the switched states?

AF domain wall resistance is likely one of the parameters contributing to the magnitude of the observed switching signal. Can such a contribution be estimated and compared to the presented data? Are there other phenomena that may explain the observed resistivity increase?

Following Table 5.2 and the associated discussion, can the significance of the normal vs. negative fast components of the relaxation be attributed to a different role/importance of defects, resp. heat conductivity of the film-substrate system?

Technical remarks

Fig 1.10 and 1.11: Missing scales

Section 1.3.4: Mentions about the applied current densities should be more quantitative.

p. 22: Other Antiferromagnetic Materials Materials

Table 2.1: Following A.1 the relaxation time should read 129.3 s for the slow component at 300 K.