Image the twist!

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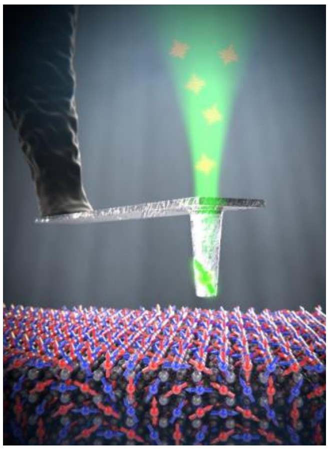
Unlike conventional electronics, magnetic materials have an appealing attribute in their non-volatility which have made magnetic recording the leading technology for data storage. From a technological point of view, there are three important challenges that will determine the future of nanoscale data storage technology: low power consumption operation, efficiency of data writing and storage density. As a result, there is a significant effort in the scientific community to engineer more efficient materials to meet the need of storing an increasingly large amount of information in a resource-efficient way. Therefore, it is our goal in this joined project proposal to focus on the nanofabrication and characterization of magnetic materials that promise to be energy efficient and reliable.
In comparison with conventional ferromagnetic materials, antiferromagnetic and non-collinear magnetic structures offer advantages, connected to reduced stray fields or ultrafast magnetization dynamics [1]. As the current-induced magnetization manipulation is tightly connected to low power consumption operation, materials with low magnetic moment offer the appealing property to allow electric-field control of magnetism via non-collinear spin order that breaks space inversion symmetry.

Amongst materials with broken inversion symmetry, multiferroics have been recently the subject of an intense research. They exhibit simultaneous ferroelectric and magnetic ordering, holding great potential for applications in energy efficient nonvolatile random access memories [2]. Their implementation in memory devices, however, will be only possible once a substantial coupling between the ferroelectric and magnetic order, the so called magnetoelectric effect, will be achieved above room temperature (RT). So far the materials exhibiting the strongest magnetoelectric coupling are those where ferroelectricity is caused by the inversion symmetry breaking induced by the appearance of a non-collinear spin structure. Typically, such a spin structure can be present in non-geometrically frustrated magnets that have very low magnetic ordering temperatures. A notable exception are materials with the formula $LBaCuFeO_5$, where L=Y or a lanthanide, such as $YBaCuFeO_5$. This material experiences two magnetic phase transitions: from paramagnetic to commensurate collinear antiferromagnetic phase at T_{N1} and to incommensurate non-collinear antiferromagnetic phase at T_{N2} [3]. In the collinear phase, the magnetic unit cell is doubled with respect to the crystal unit cell in all the three crystallographic directions. The spiral, non-collinear spin structure appearing below T_{N2} is incommensurate along the ***c*** axis and forms a circular helix with a propagation vector $k_i=(\frac{1}{2}\ \frac{1}{2}\ \frac{1}{2}\pm q)$ with a periodicity ranging from few nm to 40 nm. It has been shown that T_{N2} can be brought to the vicinity of RT by careful strain engineering [3]. However, such material can be grown only as a micron size crystals, which are not suitable for device applications. Using our expertise in nanofabrication, we have successfully grown high quality thin films (thickness ~30 nm) of $YbBaFeCuO_5$ on a $SrTiO_3$ substrate by pulsed laser deposition (PLD). Ferroelectricity measurements performed in our laboratory revealed the presence of ferroelectric order above RT, similarly to bulk samples. The same symmetry arguments used for bulk $YBaFeCuO_5$ apply to our films and suggest that the presence of ferroelectricity in the films is due to the appearance of incommensurate magnetic ordering. However, a direct measurement of the presence of magnetic ordering in such thin films is complicated by the fact that standard characterization techniques, heat capacity and neutron scattering, lack the sensitivity to probe such small sample volumes. Therefore, we plan to investigate the propagation vector(s) and the critical temperature(s) of the magnetic structure of our multiferroic thin films by means of x-ray scattering experiment at the Swiss Light Source at PSI. Such experiment, sensitive to long range ordering, can give a direct proof of the existence of a magnetic ordering in the material and therefore of its multiferroic nature. However, the scattering methods lack spatial resolution and are not suitable to investigate micron size structures for device applications.

It is therefore the goal of this project to combine the scientific expertise to grow and characterize nanostructured samples at the PSI with the expertise in nitrogen-vacancy (NV) center microscopy [4] developed by the group of Prof. Maletinsky. With the exquisite sensitivity of NV microscopy to magnetic fields scaling from milli- down to nano-Tesla combined with a high spatial resolution (10-100nm), this technique offers a unique possibility to image fine magnetic textures. It has been recently used, for example, to image magnetic skyrmions [5], magnetic spin spirals [6] or antiferromagnets [7].

Specifically, in this project proposal we propose to use the NV microscopy to image the magnetic spirals present in $YbBaFeCuO_5$ at RT. The imaging relies on presence of emanating stray fields which, in the case of $BiFeO_3$, arises from a small misalignment of the collinear antiferromagnetic ordering. Therefore, the imaging can be directly performed on $YbBaFeCuO_5$ or the magnetic stray field can be further enhanced by deposition of a thin dusting layer of a soft ferromagnet, e.g. Fe. The first milestone, namely imaging of the magnetic spirals in a RT multiferroic, will be followed by a growth optimization program aimed at enhancing the magnetoelectric coupling by adjusting the interfacial strain between the film and the substrate. The optimized sample will be subsequently nanostructured and the NV microscopy will be employed to determine the effect of spin spiral confinement. Such detailed insight into the multiferroicity in the downscaled patterns is fundamental for the device fabrication. Finally, we will aim at building a prototype magnetic memory element, based purely on a multiferroic material [8], in which we could control the magnetization of the nanostructured sample by an applied external electric field. Demonstrating a RT control of the spin spiral ordering by electric field prototype magnetic memory element would be an unprecedented breakthrough for the development of future magnetic memories.



The PhD student will:

- Grow $YbBaFeCuO_5$ thin films by PLD available at PSI.
- Characterized the grown samples by ferroelectric measurements.
- Participate in the X-ray scattering experiment at PSI to characterize the magnetic propagation vector.
- At UNIBAS, perform static NV microscopy measurements of the spin spirals states present in $YbBaFeCuO_5$ thin films.
- Optimize the growth conditions of the thin films (also by replacing Yb with other lanthanides) to enhance the magneto-electric coupling.
- Pattern the thin film in nanostructures (grown on a conducting $SrTiO_3$ substrate) by lithography techniques available at PSI and characterize them with NV microscopy measurements at UNIBAS.
- Analyze the data, present results at international conferences and publish in peer-reviewed journals.

Risk mitigation plan:

- Should initial NV magnetometry measurements on $YbBaFeCuO_5$ prove too challenging (the main risk in this proposal), alternative materials, which are relevant in the field of antiferromagnetic spintronics and readily available from PSI, will be explored. Specific examples include NiO or MnAu.

Milestones:

- Imaging of antiferromagnetic domains by NV magnetometry in the RT multiferroic $YbBaFeCuO_5$.
- Optimization of ME coupling.
- Demonstrating electric field control of magnetization in a nanostructured sample.

References:

[1] T. Jungwirth *et al.*, *New developments in spintronics based on antiferromagnetic materials show promise for improved fundamental understanding and applications in technolog*y, Nat. Phys. **14**, 200 (2018).
[2] S. W. Cheong & M. Mostovoy, *Multiferroics: A magnetic twist for ferroelectricity*, Nat. Mater. **6**, 13 (2007).
[3] M. Morin *et al.*, *Tuning magnetic spirals beyond room temperature with chemical disorder*, Nat. Com. **7,** 13758 (2016).
[4] L. Rondin *et al.*, *Magnetometry with nitrogen-vacancy defects in diamond*, Rep. Prog. Phys. **77**, 056503 (2014).
[5] I. Gross *et al.*, V. *Skyrmion morphology in ultrathin magnetic films*, Phys. Rev. Mater. **2,** 24406 (2018).
[6] I. Gross *et al., Real-space imaging of non-collinear antiferromagnetic order with a single-spin magnetometer*, Nature **549,** 252 (2017).
[7] T. Kosub *et al.*, *Purely antiferromagnetic magnetoelectric random access memory*. Nat. Com. **8,** 13985 (2017).
[8] J. T. Heron *et al.*, R. *Electric-Field-Induced Magnetization Reversal in a Ferromagnet-Multiferroic Heterostructure*. Phys. Rev. Lett. **107,** 217202 (2011).