Visualizing dynamic magnetism in nanostructures using electron microscopy

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In order to better understand the behavior of magnetic nanostructures in naturally occurring or synthetic samples, it is often necessary to investigate the underlying processes on the nano-scale. Transmission electron microscopy (TEM) allows atomic spatial resolution imaging and the development of *in situ* TEM experiments over recent years has provided fundamental insight into a range of dynamic processes. Further, combining *in situ* TEM experiments with techniques like electron holography or differential phase contrast imaging allows for visualizing of magnetization in nanostructures whilst under the influence of external stimuli; *e.g.* controlled atmospheres, temperature, etc. In this context, some examples of the use of *in situ* TEM and magnetic imaging will be presented.

Fe_3O_4 is the most magnetic naturally occurring mineral on Earth, carrying the dominant magnetic signature in rocks and providing a critical tool in paleomagnetism. The oxidation of Fe_3O_4 to maghemite (γ-Fe_2O_3) is of particular interest as it influences the preservation of remanence of the Earth's magnetic field by Fe_3O_4. Further, the thermomagnetic behavior of Fe_3O_4 grains directly affects the reliability of magnetic signal recorded by rocks. Through combining electron holography with environmental TEM and *in situ* heating, the effects of oxidation [1] and temperature (Figure 1) [2-4] on the magnetic behavior of vortex-state Fe_3O_4 NPs are visualized successfully, for the first time.

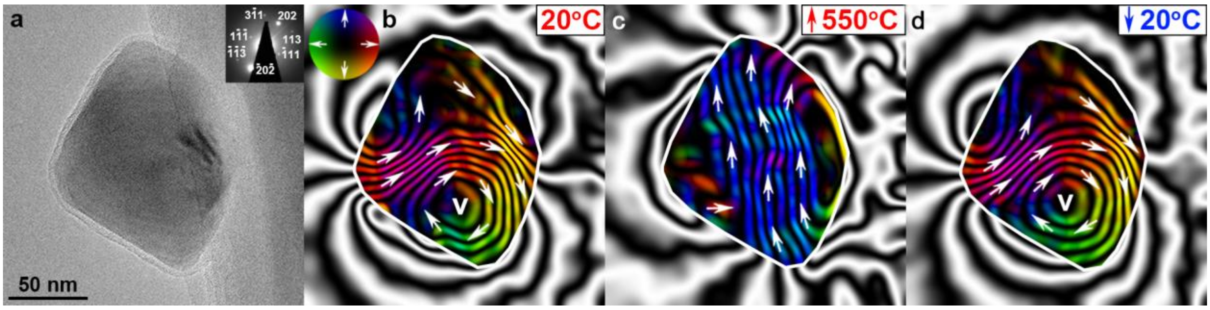

Figure 1 (a) TEM image of an Fe_3O_4 particle (~180 nm diameter), shown alongside magnetic induction maps of the Fe_3O_4 particle at (b) at 20°C; (c) during *in situ* heating to 550 °C; and (d) after cooling back to 20 °C.

Equiatomic iron-rhodium (FeRh) has attracted much interest due to its magnetostructural transition from its antiferromagnetic to ferromagnetic phase. The co-existing phases are separated by a phase-boundary domain wall (DW) and effective control over the creation and motion of these phase boundary DWs are considered desirable for potential application in a new generation of novel nanomagnetic or spintronic devices. In this context, several scanning TEM techniques are performed to visualize the localized chemical, structural and magnetic properties of a series of FeRh films [5].

[1] T. P. Almeida et al., *Nat. Commun.* 5, 5154 (2014).
[2] T. P. Almeida et al., *Sci. Adv.*, 2, e1501801 (2016).
[3] T. P. Almeida et al., *Geophys. Res. Lett.*, 41, 7041–7047 (2014).
[4] T. P. Almeida et al., *Geophys. Res. Lett.*, 43, 8426-8434 (2016).
[5] T. P. Almeida et al., *Sci. Rep.*, 7:17835 (2017).