Aberration corrected views into the nano-world

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Harnessing the next generation of functional materials requires understanding structural, physical, electronic and even magnetic properties at the nano-scale, in real space. Aberration corrected scanning transmission electron microscopy (STEM) combined with electron energy-loss spectroscopy (EELS) can probe structural, chemical, and electronic properties with atomic-level resolution, and now they can also provide magnetic information at this length scale in exquisite detail [1-3]. This talk will review a few examples of applications of STEM-EELS to complex oxide low dimensional systems such as interfaces or nanostructures. Avenues to explore magnetism in low dimensional materials will be discussed, including imaging modes sensitive to magnetic properties such as orbital moment or spin [2]. Through the use of electron magnetic circular dichroism (EMCD) [1], we will show how sub-nanometer real-space characterization of magnetism is possible. In magnetite Fe_3O_4 iron-oxide nanoparticles capped with organic acids we not only find that the surface of the nanoparticles is ferromagnetic but, combining the results with density-functional calculations, we establish how magnetization is restored in the surface layer. The bond to the organic acid prevents further oxidation to Fe_2O_3 and results in O-Fe atomic configuration and distances close to the bulk values [3]. Other examples will include explaining the origin of the unexpected ferromagnetism in ultrathin $LaCoO_{3-x}$ (LCO) films. Bulk LCO is non-magnetic and fully stoichiometric, but in thin films, epitaxial strain is released through local lattice expansion at ordered oxygen-deficient atomic planes. The vacancies lead to excess electrons in the Co *d*-states, resulting in ferromagnetic ordering. The ensuing electron doping should result in metallic behavior but, on the contrary, the films are insulating. The vacancy superstructures disrupt the band structure causing the appearance of Peierls-like minigaps. On strain relaxation, these minigaps trigger a nonlinear rupture of the energy bands, resulting in the observed insulating behavior [4]. We conclude that oxygen vacancies complement strain as a major controllable degree of freedom that can be used to engineer novel behavior in complex-oxide films.

[1] P. Schattschneider et al., *Nature* 441 (2006) 486.
[2] J. Gazquez et al. *Nano letters* 11 (2011) 973.
[3] J. Salafranca et al., *Nano Letters* 12 (2012) 2499.
[4] N. Biskup et al., Phys. Rev. Lett. 112 (2014) 087202.
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