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Abstract

Motivated by a theoretical study published in 2009 [1], the HE3115 project aimed at investigating the magnetic properties of Fe nano-structures grown on the Ru(0001) and Rh(111) substrates. According to calculations, a spin-spiral ground states should be present in extended Fe monolayer islands on Rh(111) and Ru(0001) with wavelengths up to 1.2nm. The spiral state arises as a consequence of the topological frustration of Fe atoms on the triangular lattice of these surfaces, of the antiferromagnetic (AFM) coupling, and finally of exchange interaction beyond nearest neighbours. As a result of this complex interplay, the magnetic structure is predicted to be a 120° Néel structure in case of Fe on Ru(0001) and a double-row-wise AFM structure in case of Fe on Rh(111) (combination of two spin spirals). Thus, for both substrates Fe islands are expected to show AFM alignments of moments.

The experiments during HE3115 were successful in several aspects: (i) Compact islands of Fe on both Ru(0001) and Rh(111) could be produced, in-situ, and studied in both morphology and magnetism; (ii) The magnetic coupling between Fe atoms in compact Fe islands has been found to be different compared to bulk. In particular, a very low average magnetization has been measured, even 10 times smaller than bulk, pointing to an AFM rather than FM coupling; (iii) The addition of some degree of disorder in the structure by allowing the Fe-Fe distances to vary randomly has revealed to lead to a weaker AFM coupling.

Experiments

The techniques of choice for our measurements were x-ray magnetic circular dichroism (XMCD) and x-ray magnetic linear dichroism (XMLD). The former provides quantitative information on the orbital and spin moment of the Fe atoms with moments aligned along an external magnetic field. The latter instead is useful to get information on the direction of the spins which are AFM coupled and were measured without field. Measurements have been done with and without magnetic field, at various angles between sample normal and magnetic field and at variable temperatures between 10K and 300K. Very important, we could verify the structure of islands grown at room temperature prior to magnetic characterization by *in situ* STM as shown Fig. 1 (a-b). On Rh(111) the islands were found to be of monolayer (ML) height whereas on Ru(0001) the islands have just started to form the second layer. However, the amount of material in the second layer is negligible compared to that in the monolayer. The following main investigations have been done:

Fe compact islands: A very small dichroism has been found for compact Fe islands on both substrates, with an XMCD/XAS ratio about a factor of 10 smaller than the bulk value of Fe (images (c) and (d)). This indicates a very low average Fe spin moment and therefore a non-FM coupling of the spins. A finite dichroism in the presence of non-FM coupling could be generated by uncompensated Fe spins due to the finite size of the island, which is not necessary an integer multiple of the AFM unit cell. Also to consider in case of Fe islands grown on the Ru(0001) substrate, the small amount of Fe atoms grown in the second layer, which might be FM coupled.
The variation of magnetization with temperature did not show signs of a AFM to FM transition. A slight decrease of the magnetization with temperature was instead observed, and no magnetization was found in absence of an external magnetic field. Both findings are typical for paramagnetic systems, supporting the idea that the observed dichroic signal comes from the uncompensated spins at the islands edges.
Studies of linear dichroism have also been done on these systems, with the idea to reveal anti-ferromagnetic alignment of the Fe spins. In this case, data evaluation is still in progress.

Low-temperature grown Fe thin films: Fe impurities were deposited at 10K on both Ru(0001) and Rh(111). For increasing number of atoms on the sample the system's magnetic properties were recorded in a 5T magnetic field, in a range of coverages between 0.5% of a ML and more then a full ML, which allows to monitor how the magnetization changes when the average Fe-Fe coordination is increased. The results are shown in (e) and (f). For very low coverages, corresponding to isolated atoms, in both substrates a value of the XMCD/XAS at the L_3 edge similar to the Fe bulk value was found. With increasing coverage a gradual decrease is observed which in the case of Ru(0001) continues until saturation at a value of about 1/3 the Fe bulk. On the Rh(111) instead the initial decrease of the magnetization continues down to a minimum value corresponding to ½ of the Fe bulk value at 0.4ML but then the magnetization rises again. This minimum seems to be the crossover between AFM and FM behavior and might coincide with the formation of a second layer of atoms which interact ferromagnetically. The fact that we do not see the rising of magnetization in case of Ru(0001) is still not completely understood at the moment, but could be due to a stronger AFM coupling. Theoretical simulations are under way to understand these effects.

Comparison between the two systems: When comparing the magnetic behavior of compact islands and low temperatures deposited Fe thin films, it becomes clear that AFM coupling is maximized on the compact islands. In compact Fe islands in fact the Fe-Fe distance is fixed by the substrate, since the islands are grown epitaxially and uncompensated spins are only found at the islands edges or in a second layer of atoms. In correspondence to the Ru and Rh lattice parameters an AFM coupling is expected between Fe atoms.
For low temperatures grown films instead, the atoms do not diffuse over the substrate but simply land and get immobile immediately. This means that the distribution of Fe-Fe average distances is quite large which makes the growing film very disordered. Many of the spins will be uncompensated giving an average value of the magnetization smaller than bulk but still much larger than what is found in compact islands.
Further data analysis will be done over the following months to extrapolate quantitatively spin and angular moment of the Fe in the different systems and also to better understand the data obtained with linear-polarized light.

References

[1] B. Hardrat, A. Al-Zubi, P. Ferriani, G. Bihlmayer, S. Blügel, and S. Heinze, *Phys. Rev. B* **79**, 094411 (2009).

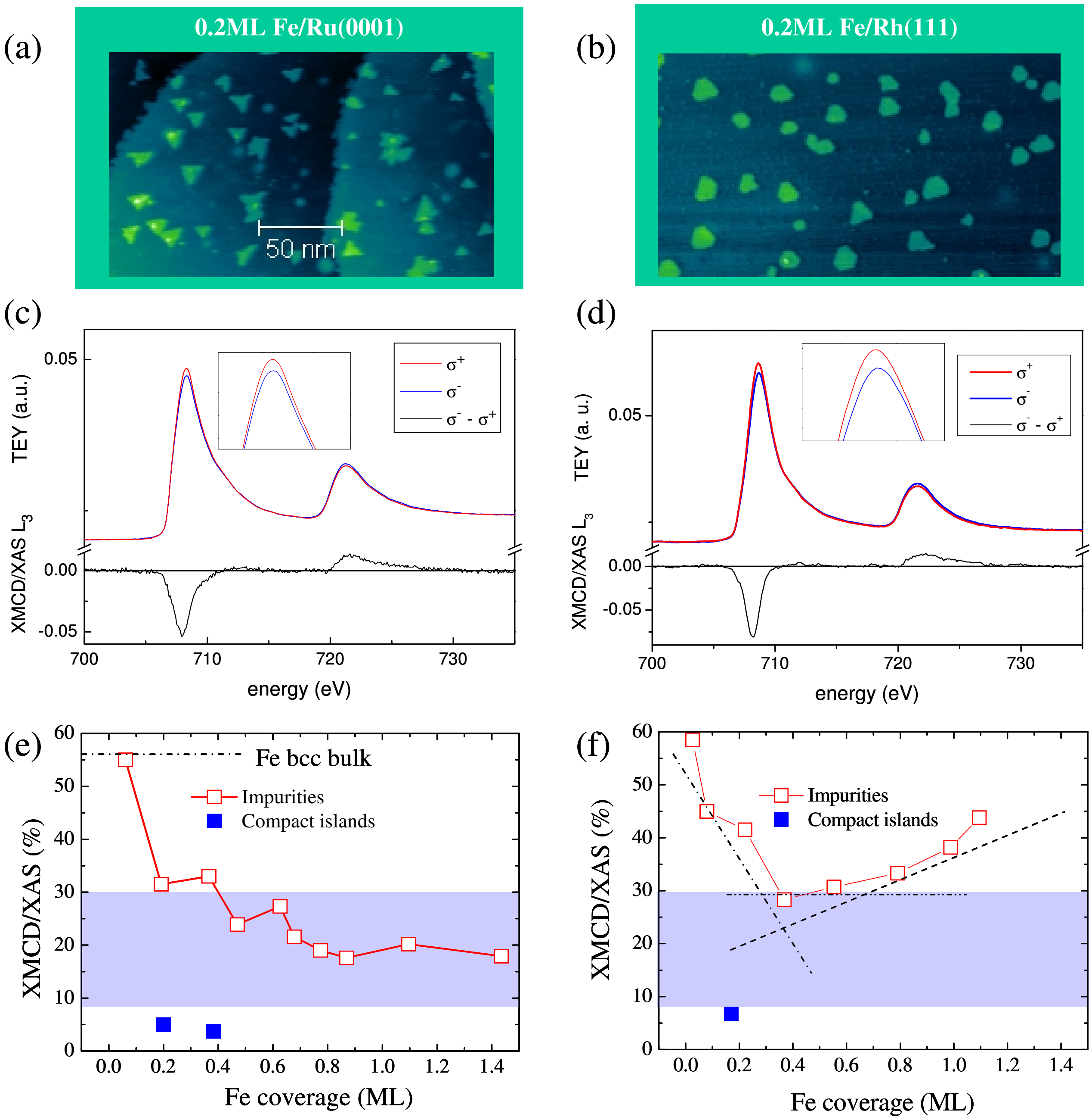

Figure 1 Compact Fe islands grown at 300K on Ru(0001) (a, c) and Rh(111): (a-b) STM topographies; (c-d) X-ray absorption at the Fe L_{23} edges and X-ray magnetic circular dichroism signal normalized at the L_3 absorption edge. The magnetic measurements were made at a temperature T=10K with a 5T magnetic field applied parallel to the sample normal; (e-f) XMCD/XAS at the L_3 absorption edge for Fe impurities deposited at 10K on Ru(0001) (e) and on Rh(111) (f), for different Fe coverages. For comparison the according values of the compact Fe islands are shown in blue.