AFM techniques for atomic- and subatomic-scale imaging and manipulation

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We have used the $p(2\times1)$ Cu(110):O surface [1] as a venue for two different low-temperature nanomanipulations with non-contact atomic force microscopy (NC-AFM) in UHV: 1) Cu atoms rearranged by vertical manipulation [2], left panel of Fig.1, and 2) magnetic Co atoms rearranged by lateral manipulation [3], right panel of Fig.1. In 1) a vertical manipulation resulted, without tip apex change, in "writing" letter "X" with Cu adatoms on the surface, Fig.1 i-ii). The process can be quantitatively understood in terms of a 4-state model, Fig.1 iii). We have calculated the energy barriers separating the states and, using kinetic Monte-Carlo, have constructed a model which enabled us to determine the deposition and extraction probabilities in agreement with experimental observations. In 2) two very different lateral Co manipulations resulted in either a fairly straightforward manipulation by one lattice site, Fig.1 iv a-b), or a delocalization manipulation where the Co adatom followed a smeared-out manipulation trajectory with the Co atom delocalized over roughly six substrate Cu atoms, Fig.1 iv c). This latter delocalized state remained (meta)stable over macroscopic time. The calculated PES, Fig.1 iv d), indicates very weak corrugation in some parts and very substantial corrugation in other parts. The calculations show that the tip-assisted delocalization manipulation is a consequence of $[Ar]d^8 \rightarrow [Ar]d^7$ modification of the spin state of the manipulated Co atom rendering it less reactive and hence more easy to manipulate, a fact which may have spintronics consequences. However, in order to rationalize the experimentally observed elliptical manipulation trajectories, an additional modulating potential is needed. We argue that this long-ranged modulation potential is created via Friedel oscillations [4] of the metal charge densities generated by the other Co atoms present on the surface. These additional Co atoms are repositionable by ordinary lateral manipulations giving access to different delocalization scenarios. In addition, simulations predict that the different spin-states of the Co atom can be imaged with sub-atomic resolution by STM [5].

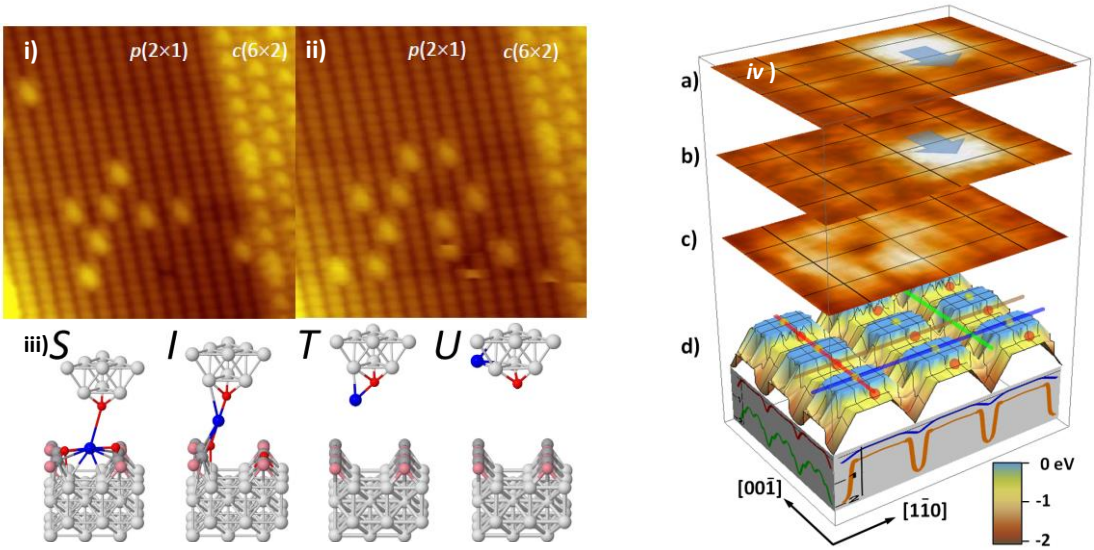

Fig1. Formation of nanostructures on $p(2\times1)$ Cu(110):O surface by NC-AFM. Left: i) - ii) experimental images of Cu atoms manipulated by vertical manipulation and elucidation of the process by a 4-state, iii), computer model. Right: Experimental images of the "delocalization", iv c), and lateral manipulation, iv a-b), of a Co atom and the corresponding calculated PES, iv d), exhibiting both extremely weakly corrugated (≈0.1eV; red and blue lines) and heavily corrugated (≈2eV; green and brown lines) portions.

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