

One-, two- and three-dimensional electronic states observed with STM

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Since scanning tunneling microscopy (STM) is based on measurement of the tunneling current, STM can be used not only for studying the surface geometry but also the electronic density of states. In the most simple approximation [1], which is found to be valid for all the systems presented here, the tunneling current is determined by the local density of states of the sample at the centre of curvature of the tip. This implies that STM is mainly sensitive to states protruding far into the vacuum above the sample; these can be either surface states localized there or bulk states with high perpendicular momentum, and, hence, low momentum parallel to the surface, i.e., states near the centre of the surface Brillouin zone $\bar{\Gamma}$.

It is well-known that the sp-like surface states on the (111) surfaces of group Ib metals (Cu, Ag, and Au) can be easily detected with STM and standing waves caused by scattering at step edges [2,3], adatoms [4], surface alloy atoms [5] as well as subsurface impurities [5] can be imaged. Although d-states are much more localized, some surface states which are d-like near the atomic cores protrude sufficiently far into the vacuum for being detected by STM, usually by scanning tunneling spectroscopy. Such states have been observed on bcc Fe(100) [6,7] and Cr(100) [6,8] and can be used as convenient markers for distinguishing between the pure surface and alloyed or adsorbate-covered surfaces where the surface state is usually either shifted to other energies or suppressed.

Being based on d-states, the surface state of Fe(100) is much more localised at individual atoms than the sp-like states mentioned above. This gives rise to interesting localisation effects; it is even possible to confine the Fe(100) surface state in single zig-zag rows of Fe atoms, whereby a one-dimensional state (chain state) is formed. Ab-initio calculations show that the confinement leads to tilting of the d_{z^2} orbitals in a way to straighten out the zig-zag structure of the rows of the Fe atoms supporting it, creating nearly linear features in a density of states map or STM topograph [7].

Whereas it is a quite trivial fact that much of the tunneling current stems from bulk states, the possibility of studying interference phenomena of bulk states on metals by STM has been suggested [9] and demonstrated experimentally [10] only recently. It could be shown that Ar-bubbles below Al surfaces act as efficient scatterers of electrons, creating one-dimensional quantum wells between the upper surface and the parallel upper side of the scatterer. Although the two degrees of freedom parallel to the surface are not confined, STM selects only those states with negligible parallel momentum, allowing us to observe an essentially one-dimensional scattering problem, where the density of states varies strongly with energy. While the depth of the scatterers (width of the quantum well) can be determined from the energy levels of the quantum well states measured by $z(V)$ tunneling spectra, STM images allow to determine the shape of the scatterers. Simulations of the three-dimensional scattering problem assuming a free electron gas yield good agreement with experimental results and also show that the interference patterns observed by STM correspond well to the upper surface of the scatterer [10].

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