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AFM/STM with sub-Angstrom modulation.

MARKUS TERNES, IBM Almaden Research Center and EPF Lausanne

Atomic manipulation of single atoms and molecules by scanning probe microscopy enables the assembly of structures at the single-atom scale - the ultimate lower size limit. However, it has been difficult to answer the simple question: How much force does it take to manipulate atoms and molecules on surfaces? To address this question, we combine scanning tunneling microscopy and frequency modulated atomic force microscopy. To enable simultaneous detection of the tunneling current and frequency shift we utilize the q-plus sensor design, in which a metallic STM tip is mounted on a cantilever made from a quartz tuning fork. The instrument operates in ultra-high vacuum at liquid helium temperature. High mechanical stability together with a stiff cantilever design, which avoids snap to contact between sample and tip, allows us to use very small modulation amplitudes of 25 pm normal to the surface. To detect such a small amplitude with a piezoelectric cantilever requires a low-temperature preamplifier stage. Mapping the frequency shift at different heights above the sample surface allows us to calculate the vertical forces acting between tip and surface. This data is then used to determine the full 3D interaction potential between the tip and a single adsorbate on a clean metallic surface by integrating the forces normal to the surface. A small amplitude is essential to achieve 10 pm resolution in all spatial directions necessary to discriminate between long range and short rage forces. With this method we are able to determine the vertical and lateral forces that are required to move individual cobalt (Co) atoms and carbon monoxide (CO) molecules across a copper (111) surface. The lateral forces, which are responsible for moving the adsorbates, are one to two orders of magnitudes smaller than the forces that act in conventional atomic force microscopy with atomic resolution.