MAR08-2007-001468

Abstract for an Invited Paper
for the MAR08 Meeting of
the American Physical Society

Three-Dimensional Force Imaging and Quantification with Atomic Resolution

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Atomic resolution images in noncontact atomic force microscopy (NC-AFM) reflect planes of constant frequency shift. To draw conclusions on the chemical activity at specific surface sites, however, the force acting between tip and sample should be known locally rather than the frequency shift. This is not an easy translation due to the non-linear nature of the relationship between the two. To overcome this problem, several groups have developed an extension to NC-AFM, *dynamic force spectroscopy*, which allows the precise, distance-dependent measurement of tip-sample forces. The forces are determined from frequency shift versus distance curves by mathematical analysis. Even though this approach had some success, prior attempts resulted either only in two-dimensional atomic resolution force xz-maps or in data sets of relatively low resolution, as long-term drift stability has been a problem. Using our recently completed home-built low temperature, ultrahigh vacuum NC-AFM, we were able to map the complete three-dimensional (3D) force field over a surface. Simultaneously, the tip-sample interaction potential and the energy dissipation of the oscillation process were recorded. As a test material, we used highly oriented pyrolytic graphite (HOPG) in order to study the atomic-scale origins of its qualities as a solid lubricant. Individual data points have been acquired over a surface area comprising several unit cells in a 3D grid with less than 6 pm grid size in all directions. From this data set, representations of cuts in any direction can be produced. While constant height images show atomic resolution with pN force resolution, vertical cuts visualize how the attractive force fields of the atoms extend into the vacuum space. We expect that the technique will find applications in fields of science where a local knowledge of interaction forces is beneficial, such as catalysis, chemical imaging, thin film growth, device fabrication, and tribology.