Frequency-Modulation Atomic Force Microscopy: A New Tool For Atomic Imaging And Manipulation In Any Kind Of Surfaces

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This presentation reviews, from a theoretical perspective, our current understanding of Frequency-Modulation Atomic Force Microscopy (FM-AFM, also known as Non-contact AFM)[1,2]. This dynamical operation mode has fulfilled the long-standing goal of achieving true atomic resolution with AFM on a great variety of samples, including semiconductor, metallic and insulating (oxides, alkali halides) surfaces. At variance with the standard amplitude modulation (tapping) AFM technique, in FM-AFM the cantilever is kept oscillating with a fixed amplitude at its resonance frequency. This resonance frequency depends on the forces acting between the tip and sample. The spatial dependence of the frequency shift, the difference between the actual frequency shift and that of the free lever, is the source of contrast. An image is formed by profiling the surface topography with a constant frequency shift.

Motivated by a brief experimental review, we present different theoretical approaches, ranging from analytical approximations, numerical simulations of the equation of motion, first principles calculations of tip-sample forces [3,4,5] and the simulation of the cantilever dynamics including the control electronics [6] in order to understand the origin of the image contrast. After a description of the general relation between frequency shifts and tip-sample interactions, we focus on the discussion of the role of short-range forces (like chemical interactions between tip and surface dangling bonds and short-range electrostatic forces) in the atomic contrast observed in semiconductor, ionic and metallic surfaces. Particular attention is paid to the experimental separation of the contribution from long-range interactions and the inversion procedures developed to extract the interaction potential from the measured frequency shift. Based on the previous analysis, noise considerations and the large experimental evidence accumulated, we discuss possible optimal conditions (cantilever stiffness and frequency, vibration amplitude, tip preparation, frequency shift set point, bias voltage, etc) for operation with enhanced atomic resolution. The interplay between LR and SR forces in the corrugation, and, in particular, its role in extending the stable operation conditions and the explanation of the contrast reversal observed under certain operation conditions is studied.

Finally, we address recent experiments [7] that show both vertical and lateral manipulation of individual atoms on a semiconductor surface with a pure force control. These results open the way to extend our atomic scale manipulation capabilities to the technologically relevant insulating surfaces.

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