Quantitative force imaging of the atoms in epitaxially grown graphene

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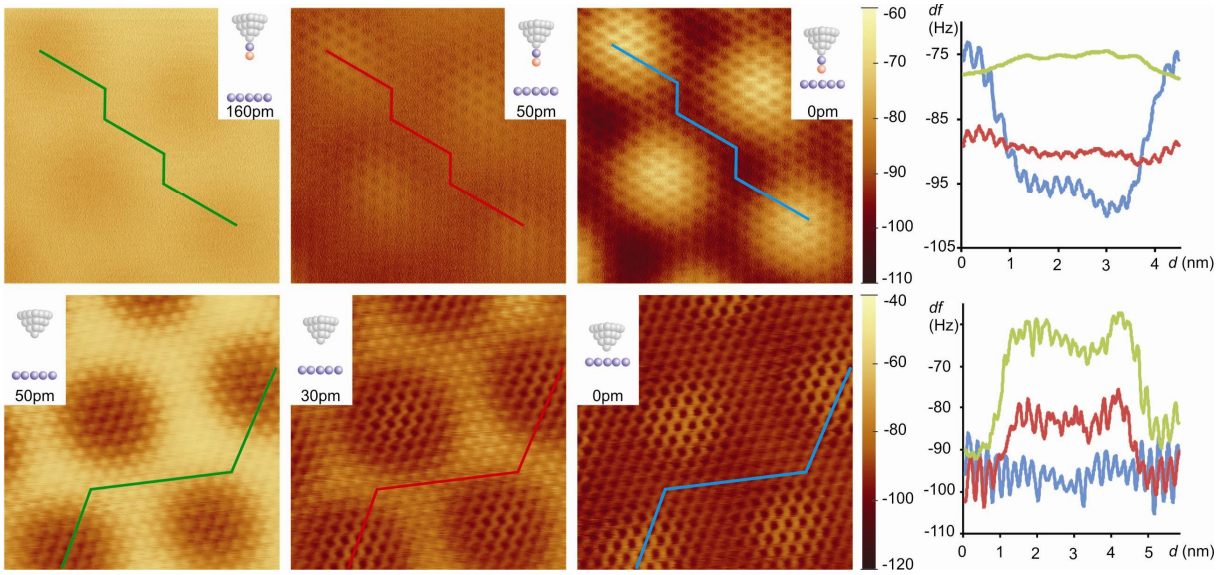
Scanning probe microscopy is an indispensable tool in order to study both the atomic structure as well as the electronic properties of graphene in real space. A crucial question regarding the atomic structure is how to relate the periodic contrast in the acquired images to the true position of the C atoms and the hollow sites [1].

Using non-contact atomic force microscopy with very small modulation amplitudes (~150pm) we measured the frequency shift *df* over epitaxially grown graphene on Ir(111) at various tip-sample distances d_{ts}. This was done both using a non-reactive, carbon monoxide (CO) terminated tip as well as a reactive, metallic tip. By simultaneous measurement of the current we could link all features in *df* to their position within the moiré unit cell.

In the figure below the frequency shift *df* recorded with the different tips is plotted for various tip sample distances. For the CO tip at large d_{ts} (top row, left) only large scale attraction (more negative *df*, dark) is observed that the CO tip experiences on the on top positions of the moiré unit cell. Here d_{ts} is locally reduced due to the outward buckling of the graphene. At smaller d_{ts} a chicken-wire pattern of repulsive interaction (less negative *df*, bright) is observed, which we attribute to the graphene lattice. The metal tip case (bottom row) is remarkably different. At large d_{ts} the tip experiences an attractive force on the atomic backbone of the graphene, before it changes to repulsive at very small d_{ts}.

Furthermore we quantified the different forces by measuring spectra of *df* vs d_{ts} with both the CO and the metal tip on different sites above the graphene and integrating this to the force. This led to an unambiguous determination of the atomic and hollow positions in graphene. This technique allows the study of the chemistry at the graphene edges and provides a basis for the quantum mechanical understanding of the nature of these forces.



References

[1] M. Ondracek et al., Phys. Rev. Lett. **106**, 176101 (2011).