Open Loop Heterodyne KPFM for Quantitative Electrostatics and Potential Dynamics

Hugo Valloire[1], Christian Loppacher[1], Sylvain Clair[1], Benjamin Grévin[2], Laurent Nony[1]

[1] Aix Marseille Université, Univ Toulon, CNRS, IM2NP, Marseille, France
[2] Institut Néel, UPR 2940 CNRS, Grenoble, France

Kelvin probe force microscopy (KPFM) is used to probe local electrostatic properties through the tip–sample contact potential difference (CPD). In heterodyne KPFM, mechanical oscillation and voltage modulation are combined to detect electrostatic signals at the resonance of the second eigenmode of the cantilever (1). In this contribution, a quantitative framework for open-loop heterodyne measurements and a dual-heterodyne KPFM (DHe-KPFM) implementation for reconstructing periodic CPD dynamics are presented.

For amplitude-modulated heterodyne KPFM (AM-He-KPFM), the tip–surface capacitance gradient is described using a non-truncated Taylor expansion. Its convergence is established for a realistic capacitance model, and criteria for assigning truncation regimes are defined (2). Using this treatment within the bimodal virial and power-balance formalism, the electrostatic interaction is linked to the frequency shift and dissipation of the first eigenmode of the cantilever and to the amplitude and phase of the second. An inverse heterodyne effect is identified, whereby the second-mode motion acts back on the first eigenmode through inter-mode energy exchange (3). A pronounced resonant signature in the dissipation channel, with a weaker contribution to the frequency shift, is predicted by the model and confirmed by UHV experiments.

To identify the temporal signature of the CPD, successive CPD harmonics are selectively transferred to a cantilever resonance through double heterodyne mixing in DHe-KPFM (4). The scheme is implemented by synchronizing an arbitrary waveform generator (HDAWG) with a single external lock-in amplifier (HF2LI), replacing the original two-lock-in configuration while preserving phase coherence across the Fourier components. Their amplitudes and phases are used to reconstruct the periodic waveform by an inverse Fourier transform. Reconstruction of the imposed potential dynamics is validated using an arbitrary periodic voltage applied to the tip. These developments support quantitative interpretation of heterodyne electrostatic signals and provide a basis for future time-resolved studies of photoinduced charge dynamics.

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