Canadian Association of Physicists

Association canadienne des physiciens et physiciennes

Contribution ID: **1956** Type: **Oral (Non-Student) / Orale (non-étudiant(e))**

A New Pathway for Robust High-Resolution Imaging and Quantitative Force Spectroscopy in Vacuum: Tuned-Oscillator Atomic Force Microscopy

Tuesday 12 June 2018 11:45 (15 minutes)

Since the first demonstration of atomic resolution in ultra-high vacuum more than twenty years ago, frequency modulation-based noncontact atomic force microscopy (FM-NC-AFM) has significantly matured and is now routinely applied to study problems that benefit from high-resolution surface imaging. In FM-NC-AFM, control of the tip's vertical position is accomplished by detecting a shift in the cantilever's resonance frequency upon approach to the sample. Consistently ensuring reliable distance control during extended data acquisition periods has nevertheless remained challenging, as most FM-mode-based control schemes employ three feedback loops that may interfere. As a consequence, sample throughput in FM-NC-AFM is often low compared to ambient condition AFM, where the easy-to-implement amplitude-modulation (AM) control scheme is predominantly used. Transfer of the AM methodology to high-resolution measurements in vacuum is, however, difficult as with AM-AFM, instabilities during approach are common; in addition, the lack of viscous air damping and the related significant increase of the cantilever's quality factor generates prolonged settling times that cause the system's bandwidth to become impractical for many applications. Here we introduce a greatly simplified approach to NC-AFM imaging and quantitative tip-sample interaction force measurement that prevents instabilities while simultaneously enabling data acquisition with customary scan speeds by externally tuning the oscillator's response characteristics [1]. After discussing background and basic measurement principle, examples for its application to characterize layered materials, thin-films, and topological crystalline insulators are provided [2-4].A major advantage of this operational scheme is that it delivers robust position control in both the attractive and repulsive regimes with only one feedback loop, thereby carrying the potential to boost the method's usability.

[1] O. E. Dagdeviren *et al.*, Nanotechnology **27**, 065703 (2016).

[2] O. E. Dagdeviren *et al.*, Nanotechnology **27**, 485708 (2016).

[3] O. E. Dagdeviren *et al.*, Physical Review B **93**, 195303 (2016).

[4] O. E. Dagdeviren *et al.*, Advanced Materials Interfaces **4**, 1601011 (2017).

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Session Classification: T2-5 Instrumentation and Imaging (DAPI) | Instrumentation et imagerie (DPAI)

Track Classification: Applied Physics and Instrumentation / Physique appliquée et de l'instrumentation (DAPI / DPAI)