Automation of topography and phase contrast measurements in tapping mode

Y.A. Bobrov[1], V.A. Bykov[1,2], S.I. Leesment[1], V.V. Polyakov[1]

[1]NT-MDT Spectrum Instruments, 124460, Zelenograd, Moscow, Russia
polyakov@ntmdt-si.com

[2]Moscow Institute of Physics and Technology, 141700, Dolgoprudny, Moscow, Russia

The idea to use oscillating cantilever for topography measurements was proposed simultaneously with AFM invention. The beginning of wide use and popularization of tapping mode (often called “semicontact mode” in Russian language) should be referred to appearance of publications [1-3]. A bit later it was accidentally found that the phase of cantilever oscillations can also be imaged in tapping mode, in some cases giving valuable contrast of material properties [3]. Dozens of AFM modes were introduced since that time, but tapping (incl. phase imaging) still remains the most frequently exploited one. Tapping mode also serves as the basis for a variety of more complex AFM modes like Kelvin probe force microscopy (KPFM), electric force microscopy (EFM), magnetic force microscopy (MFM), etc. as well as for rapidly growing family of optical nanospectroscopy methods like scattering scanning near-field optical microscopy (s-SNOM) in visible, infrared and terahertz spectral ranges.

At the same time, our analysis shows that more than one fifth of AFM images published in peer-reviewed journals contain typical artefacts associated with switching from attractive to repulsive regimes of interaction of cantilever and surface, probe parachuting effect and incorrect setting of feedback gain value. This disheartening situation motivated the development of “ScanTronic” system which allows to automatically adjust the amplitude of cantilever oscillations, scan rate, set point and feedback gain values in tapping mode AFM to provide reliable artifacts-free results.

Parachuting effect (Fig. 1a) that occurs at sudden detach or collision of cantilever with the sample cause the most prevalent artifacts in both topography and phase images in tapping mode. It becomes extremely critical if high aspect ratio probes are used. Analysis of this effect shows allowable ranges of cantilever oscillations amplitude, scan rate, set point and feedback gain values – following these limitations, one avoids artefacts of this kind. We also propose simple yet highly effective way (Fig. 1b) to compensate parachuting artefacts in AFM images by use trace and retrace scan lines.

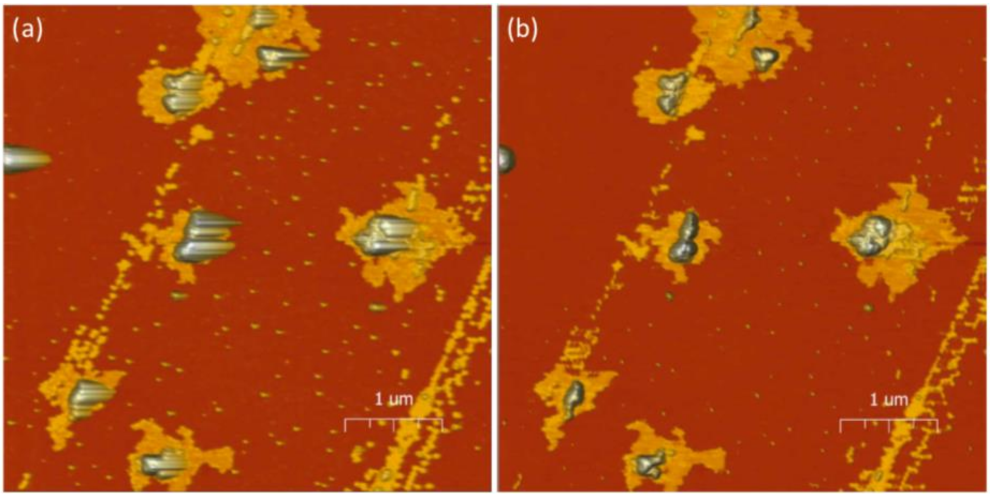

Figure 1. Fluoroalkanes F14H20 on Si imaged in tapping mode: (a) parachuting artefacts, (b) *in-situ* parachuting artefacts compensation using trace and retrace scan lines.

General consideration of AFM feedback system operation gives quite elementary but very representative relation between the error signal value $e(x)$ and feedback gain k_{FB}, scan speed dx/dt and topography gradients dH/dx: $e(x) \sim k_{FB}\cdot(dx/dt)\cdot(dH/dx)$. This relation yields that error signal can be decreased while scanning rough topographies by adaptive control of scan speed. This option, that we implement in our microscopes under “safe probe” name, allows to minimize the risk of damage of the probe and consequently decrease average cantilever consumption per single measurement session.

Switching between attraction and repulsive regimes [4] is another often source of artefacts in tapping mode. It is well known that phase signal can be used to recognize the type (sign) of interaction between cantilever and a surface that take place during experiment. We show the way of automated control and pre-adjustment of interaction regime in tapping mode and demonstrate its effectivity.

This considerations form the basis of algorithms realized in our “ScanTronic” module. One of numerous examples of “ScanTronic” applications for studies of sPS-PVDF structure is shown in Figure 2.

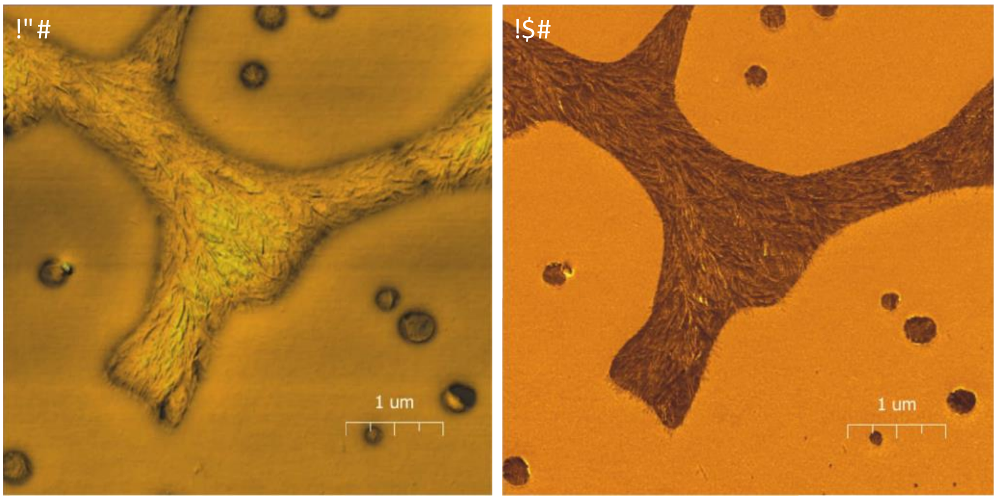

Figure 2. sPS-PVDF topography and phase contrast. Cantilever oscillations amplitude, scan rate, set point and feedback gain values are adjusted automatically by “ScanTronic”.

Thus the system for automated adjustment of scanning parameters in tapping mode is developed and corresponding physical principles are discussed. We present a number of examples showing that these principles and measures combined with linear control theory techniques and machine learning algorithms make it possible to literally completely automate the adjustment of scanning parameters in tapping mode. This approach drastically increases the quality of phase contrast images as well.

Further development of “ScanTronic” will allow to automate the adjustment of scanning parameters in more complex AFM modes for automated imaging of electrical, magnetic and other properties of surfaces with (sub-)nm level spatial resolution.

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