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Drift-insensitive distributed calibration of probe microscope scanner in nanometer range: Virtual mode

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ABSTRACT

A method of distributed calibration of a probe microscope scanner is suggested. The main idea consists in a search for a net of local calibration coefficients (LCCs) in the process of automatic measurement of a standard surface, whereby each point of the movement space of the scanner can be characterized by a unique set of scale factors. Feature-oriented scanning (FOS) methodology is used as a basis for implementation of the distributed calibration permitting to exclude *in situ* the negative influence of thermal drift, creep and hysteresis on the obtained results. Possessing the calibration database enables correcting in one procedure all the spatial systematic distortions caused by nonlinearity, nonorthogonality and spurious crosstalk couplings of the microscope scanner piezomanipulators. To provide high precision of spatial measurements in nanometer range, the calibration is carried out using natural standards – constants of crystal lattice. One of the useful modes of the developed calibration method is a virtual mode. In the virtual mode, instead of measurement of a real surface of the standard, the calibration program makes a surface image "measurement" of the standard, which was obtained earlier using conventional raster scanning. The application of the virtual mode permits simulation of the calibration process and detail analysis of raster distortions occurring in both conventional and counter surface scanning. Moreover, the mode allows to estimate the thermal drift and the creep velocities acting while surface scanning. Virtual calibration makes possible automatic characterization of a surface by the method of scanning probe microscopy (SPM).

1. Introduction

By using several techniques embedded into the feature-oriented scanning (FOS) methodology [1], a new distributed approach to calibration of the probe microscope scanner is suggested [2,3]. The essence of the developed approach is that instead of characterizing the whole movement space of a probe microscope scanner by three calibration coefficients K_x, K_y, K_z [4], each point (x, y, z) of this space is characterized by its own unique triplet of local calibration coefficients (LCCs) $K_x(x, y, z), K_y(x, y, z), K_z(x, y, z)$ [2]. As a result, it is possible to correct all spatial systematic distortions caused by nonlinearity, nonorthogonality and spurious crosstalk couplings of the microscope scanner X, Y, Z piezomanipulators. In the real mode [3], application of the FOS approach [1] and the methods of counter-scanning [5] permits eliminating *in situ* the negative influence of thermal drift [6], creep [7], and hysteresis [8] on the distributed calibration results.

A reference surface used for calibration should consist of elements, called hereinafter features, such that the distances between them or their sizes are known with a high precision. The corrected coordinate of a point on the distorted image of an unknown surface is obtained by summing up the LCCs related to the points of the movement trajectory of the scanner [2].

Virtual distributed calibration is such a calibration that the physical surface of a standard is substituted with a topography image

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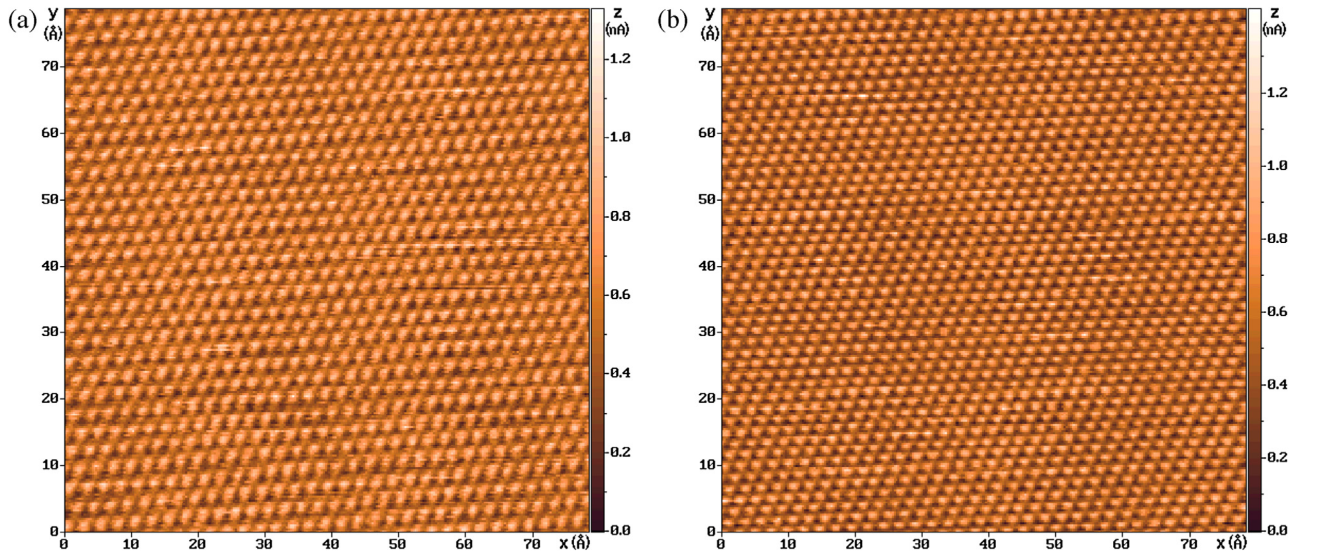

Fig. 1. Drift-distorted scans of atomic surface of pyrolytic graphite (a) direct image, (b) counter image. Measurement mode: STM, constant-height, U_{tun} = 85 mV, I_{tun} = 750 pA. Number of points in the raster: 256 × 256. Scanning step size: Δ_x = 0.306 Å, Δ_y = 0.307 Å. Number of averagings of topography height at the raster point is 15. Scanning velocity $v_x = v_y$ = 223.1 Å/s (is determined while training). CSI scanning time T_{CSI} = 6 min. Mean constant of atomic lattice equals to (a) 2.7 Å, (b) 2.2 Å; which corresponds to the relative measurement error of (a) 11%, (b) 11%.

under correction. Of course, the thermal drift and creep of the microscope can not possibly have been excluded during such sort of calibration, which is reflected in the obtained LCC and obliquity angle distributions. After the virtual calibration database (CDB) of the image under correction has been created, the nonlinear correction of the image is carried out. It does not matter for this mode which exact factors have distorted the scan under correction, *e.g.*, thermal drift, creep, or static piezoscanner nonlinearities acting together or separately.

The virtual mode is intended for simulating the process of calibration and validating the analytical solutions found in Ref. [2]. The virtual mode of distributed calibration allows thorough analysis of probe microscope scanner operation. In particular, the mode permits determination of the values and the character of raster distortions for both regular and counter types of scanning. Moreover, the virtual mode can be used to estimate the thermal drift and creep velocities, for moiré detection [9], and for automatic characterization of crystal surfaces.

2. Measurement conditions

The atomic topography of the basal plane (0001) of highly oriented pyrolytic graphite (HOPG) monocrystal was used as a standard surface. The measurements were carried out at the scanning probe microscope (SPM) Solver^{TM} P4 (NT-MDT Co., Russia) by method of scanning tunneling microscopy (STM) in the air at room temperature. In order to minimize thermal deformation of the sample, a graphite crystal of small dimensions 2 × 4 × 0.3 mm was used. Three adjacent carbon atoms (or interstices) forming an equilateral triangle ABC (see Fig. 3(a) in Ref. [2]) were selected as a local calibration structure (LCS). According to the neutron diffraction method, the HOPG lattice constant *a* (*i.e.*, side length of the ABC triangle) makes 2.464 ± 0.002 Å [10].

As the tip, a mechanically cut ⌀0.3 mm NiCr wire was used. To protect the microscope against floor vibrations, a passive vibration isolation system was employed. Moreover, the microscope was housed under a thermoinsulation hood, which also served as an absorber of external acoustic disturbances. The typical noise level of the tunneling current in the course of the measurements made about 20 pA (peak-to-peak).

During the raster scanning, the probe movement velocity at the retrace sweep was set the same as at the forward trace. Immediately before the raster scanning begins, scanner "training" was carried out [5]. The scanner training is a repeated movement along the first line, which allows to decrease creep at the beginning of the scan [7]. While training, the actual scanning velocity was also determined.

Some of the values in the sections presented below are intentionally given with a redundant number of significant digits. That will permit to compare them with the similar values obtained under different measurement conditions or in different measurement modes.

3. Almost linear raster distortions

3.1. Analysis, correction, comparison of errors of direct and counter images

STM-scans of HOPG surface distorted by drift are shown in Fig. 1. A regular (direct) surface scan and a scan counter to it [5] are given in Fig. 1(a) and Fig. 1(b), respectively. Virtual FOS [1] of the presented images allows determining a mean atomic lattice spacing as 2.734 ± 0.25 Å and 2.199 ± 0.20 Å, whence it is easy to estimate a relative measurement error as 11.0% and 10.8%, respectively. Mean spacings determined by interstices made 2.731 ± 0.25 Å and 2.197 ± 0.20 Å, relative measurement error is 10.8% and 10.9%, respectively.

In Fig. 2, shown are: partitioning of the graphite scan by an integer-valued net having square cells; "probe travellings" during the virtual calibration (compare with the trajectory of the real mode in Ref. [3]); and LCS positions for which LCCs and local obliquity angles were determined. The images in Fig. 2 correspond to the case when carbon atoms are used as features; using interstices would give a similar result. In order to decrease the influence of edge effects [7,11], features located along the image edges were excluded from consideration by setting corresponding area of distributed calibration.

Apertures [1,2] of 37 × 37 points and segments [1,2] of 25 × 25 points were used while calibrating by the direct image; 31 × 31 and 21 × 21 – while calibrating by the counter one. 1296 apertures were "scanned" on the direct image and 1849 apertures – on the counter