Methods for Vertical Drift Measurements of Scanning Probe Microscopes

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Time stability plays an important role in the applications of scanning probe microscopes (SPMs). Although SPMs integrated with a closed-loop control system could reduce the drift greatly, drift would still exist. The SPM drift in the lateral direction has been well studied, and several measurement methods have also been developed. However, due to coupling of the lateral drift, it is still difficult to determine the drift in the vertical direction. In this paper, we propose a method to measure the vertical drift of an SPM based on scanned topography images. This method considers the influence of the lateral drift. Experimental results show that the vertical drift of the SPM is non-negligible, and the vertical drift on each pixel of one scanned image is different from each other. By such a method, instability in the vertical direction of the SPM instrument could be revealed and evaluated.

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Introduction

The scanning probe microscope (SPM) has now been a significant instrument in nanoscience and nanotechnology.[1] Due to thermal noise, hysteresis and creep of the piezo-actuator, and uncontrolled tip-sample separation,[2] drift exists universally in the applications of the SPM. The occurrence of drift could affect the performance of SPM greatly, especially in fields where long time and precise positioning are indispensable, for example: physical properties measuring,[3,4] dynamic behaviors monitoring,[5,6] nanomanipulation,[7,8] *etc*. Nowadays, some SPMs are equipped with the closed-loop control.[9,10] However, drift still exists in most environments. Due to these reasons, convenient drift measurement and compensation methods are necessary.

Two methods are now commonly used for measuring SPM drift in the lateral direction: the characteristic marker method[11,12] and the image correlation method.[13,14] The former allows the lateral drift, image rotation and magnification to be determined manually, with a resolution of one pixel. The latter could obtain the lateral drift automatically with a resolution of sub-pixel. In contrast, due to coupling of the lateral drift, there still lacks an efficient and convenient method to determine the vertical drift of an SPM.[15,16]

In this paper, a simple method is proposed to determine the vertical drift of an SPM based on consecutive scanned topography images. Experiments on an atomic force microscope (AFM) were conducted to verify this method. The results show that the vertical drift of the SPM is not negligible and the drift on each pixel of one scanned image is different.

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Experimental

Drift is a composite parameter for evaluating the instrument performance. All components in the operation of the SPM could contribute to the drift. In this work, the vertical drift of the SPM is defined as the change in the vertical position of the probe tip, for a given positional setting by the instrument controller, relative to the sample. According to the principle of SPM operation, the tip-sample distance should be kept constant in topography imaging. Under such an ideal condition, the same height value should be obtained at the same sampling position when scanning under the identical settings. However, due to non-ideal feedback, coupling of the drift in the lateral direction and other reasons, the same pixel often presents different heights during consecutive scanning of the SPM with the same settings. Thus, if we could eliminate the influence of the lateral drift, the vertical drift could be determined from aligned topography images that are scanned under the same settings.

Due to its random characteristic, the lateral drift on each point of the SPM topography image is not equal. However, for simplicity, we assume that the lateral drift is identical on each point of the topography image. This assumption is verified by using the characteristic marker method.[11] Based on this assumption, we could measure the vertical drift of the SPM by the following procedures: (i) calculate the lateral drift (in pixels) between two images scanning under the identical settings by image analysis, such as image correlation method or characteristic marker method. Here, the image correlation method is selected due to its convenience. (ii) Based on the calculated lateral drift, extract and align the overlapped areas of the two topography images. (iii) Calculate the height difference of each pixel on the aligned images, which is considered to be the vertical drift of the SPM on each imaging point. (iv) Obtain the average of the height difference of each pixel. The average

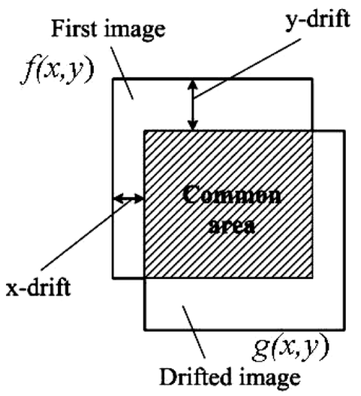

Fig. 1 Schematic diagram of the vertical drift determination for SPM instruments.

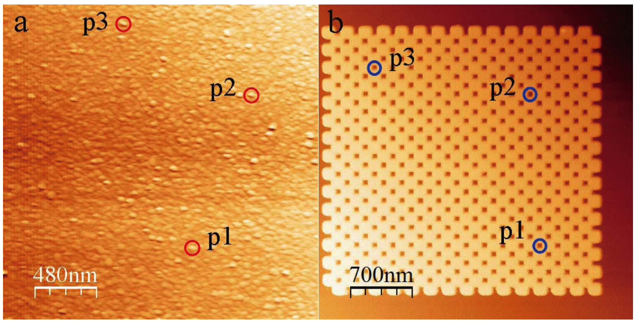

Fig. 2 AFM topography images of (a) Pt film sputtered on a silicon wafer by the contact mode and (b) periodic grating by the tapping mode. Points indicated by circles are the selected feature points.

height difference is considered here to be the vertical drift of the SPM that takes place in the interval of scanning two images. A schematic diagram of the vertical drift determination can be seen in Fig. 1.

The above computation of the vertical drift of the SPM could be performed automatically either off-line or on-line. If we denote the two topography images as $f_i = [h]_{m\times n}$, $i = 0, 1$, where h is the height data set of the sample surface topography, m and n are the pixel numbers of the images. Then, the lateral drift during the interval of the twice imaging could be obtained by[17]

$$C(u,v) = \frac{\sum_x \sum_y [f_0(x,y) - f_{0a}][f_1(x+u, y+v) - f_{1a}]}{\sqrt{\sum_x \sum_y [f_0(x,y) - f_{0a}]^2}\sqrt{\sum_x \sum_y [f_1(x+u,y+v) - f_{1a}]^2}}. \quad (1)$$

Here, subscript "a" means the average of image f_i; x and y are the indices of the rows and columns in f_i. The deviation of the maximum of the correlation matrix, $C(u,v)$, from its center is the lateral drift between the two images.

After the lateral drift is acquired, we can align the images and extract the overlapped regions out; that is

$$f_i = [h]_{m\times n} \longrightarrow f_{i|\mathrm{align}} = [h]_{(m-k)\times(n-l)}, \quad (2)$$

where k and l are the calculated lateral drifts.

Then, subtraction is applied to the two aligned images, and we obtain the vertical drift of the SPM on each imaging point,

$$[d_{xy}] = f_{1|\mathrm{align}} - f_{0|\mathrm{align}}. \quad (3)$$

The vertical drift of the SPM, d_{aver}, that takes place in the interval of the twice imaging is then calculated as

$$d_{\mathrm{aver}} = \frac{\sum_x \sum_y [d_{xy}]}{(m-k)\times(n-l)}. \quad (4)$$

Results and Discussion

Experiments were conducted to show the vertical drift of the AFM based on the method proposed above. All experiments were performed with a commercial AFM (Multimode, Nanoscope III, Veeco, Santa Barbara, CA) under the ambient condition in a clean room. A periodic grating and Pt film sputtered on a silicon wafer were tested with the tapping mode and the contact mode, respectively. Two kinds of cantilevers were used, *i.e.*, NSG-10 (NT-MDT, Moscow, Russia) for the grating and CSC11/Pt/50 (MikroMasch, Tallinn, Estonia) for the Pt film. More than 11 topography images of each sample surface were continuously acquired under the same settings for analysis. To show the change in the vertical drift with time, one firstly scanned topography image of each sample was selected as the reference image to calculate the vertical drift that occurs during the subsequent 10 images scanning. The two reference images are shown in Fig. 2.

Figure 3 shows the typical vertical drifts on the aligned pixels. It can be seen that most pixels experience a relatively consistent vertical drift, except for convex points on the sample surface of Pt and edges of the grating elements, as illustrated by the arrows. The great drifts (with either positive or negative value) in these areas could mainly be attributed to non-ideal feedback, low aligning accuracy (one pixel in our method), assumed identical lateral drift on each pixel (image magnification and rotation are neglected).

The distributions and statistic histograms of the vertical drifts on the aligned image are presented in Figs. 3 and 4, respectively. We can see that most vertical drifts on different imaging points of the sample lie in the range of several nanometers. However, there are also many points that experience very large vertical drift, which are mostly those points with large topographic variations on the sample surface, as shown in Fig. 3. This manifests that the vertical drift is not negligible, especially under the conditions that precise distance evaluations are needed. It also can be seen from Fig. 4(b) that vertical drifts of the grating sample show a bigger span, but a more regular distribution, due to the uniform surface structure and larger peak-to-peak value (about 152 nm, compared to 59 nm of the surface of Pt).

Average vertical drifts of all 10 images of the two samples were computed as a function of time, as shown in Fig. 5. The vertical drifts on three arbitrarily selected characteristic points[18] (points are shown by circles in Fig. 2) on each sample were also plotted. Some important information could be obtained from this result. First, either the average vertical drift or the vertical drift on a single feature point does not show an apparent trend in the short imaging period (about 1 h), which is different from the case of lateral drift (not shown here), which often shows a near linear variation in a short period.[8,11] Second, although there is big discrepancy between the average vertical drift and the vertical drift on an arbitrarily selected feature point, it still holds true among the feature points. This can also be seen in Figs. 3 and 4, where the vertical drifts on all imaging points are

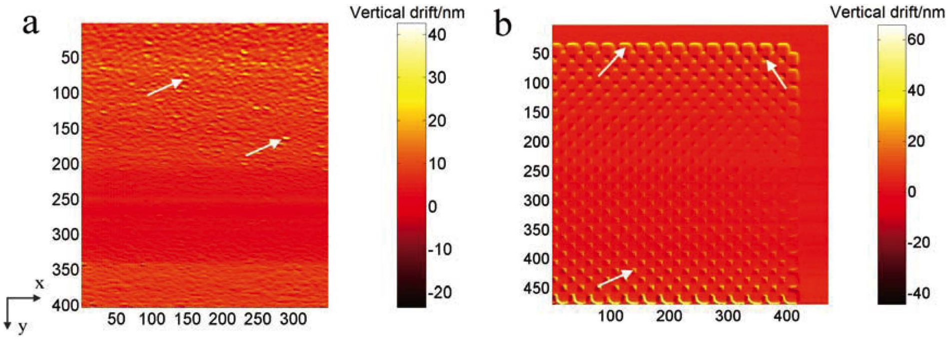

Fig. 3 Typical vertical drifts of the AFM at the aligned imaging points in scanning for (a) Pt film surface and (b) periodic grating surface. Arrows indicate that AFM would experience big vertical drift when imaging positions with abrupt changes of the surface topography. Lateral drifts calculated by image correlation analysis are: (a) 6.96 pixels in *x*-direction, –60.73 pixels in *y*-direction; (b) 34.94 pixels in *x*-direction, –42.36 pixels in *y*-direction.

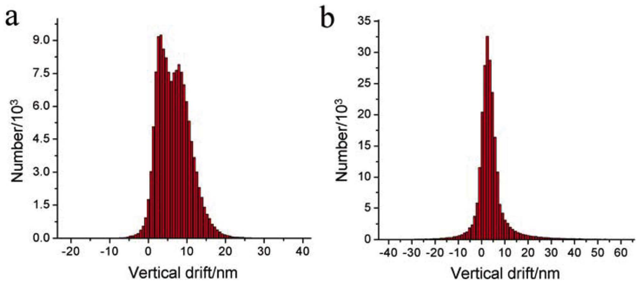

Fig. 4 (a) Histograms of the vertical drifts illustrated in Fig. 3(a). (b) Histograms of the vertical drifts illustrated in Fig. 3(b).

presented. The results demonstrate that one should be cautious when using a feature point to track the vertical drift of an SPM.

Conclusions

In conclusion, a simple method for vertical drift measurements of an SPM based on consecutively scanned topography images is proposed. Experiments and calculations show that SPM presents different vertical drifts at different imaging points during imaging. When the surface is smooth, it shows a smaller vertical drift. On the contrary, vertical drift would increase when encountering abrupt changes of the surface topography. Results demonstrate that this method could help to evaluate the instability in the vertical direction of the SPM instrument, and also the image quality. Vertical drift evaluation has significant meaning in the fields of nanomanipulation and nanoassembly where long-term local operation is often required.

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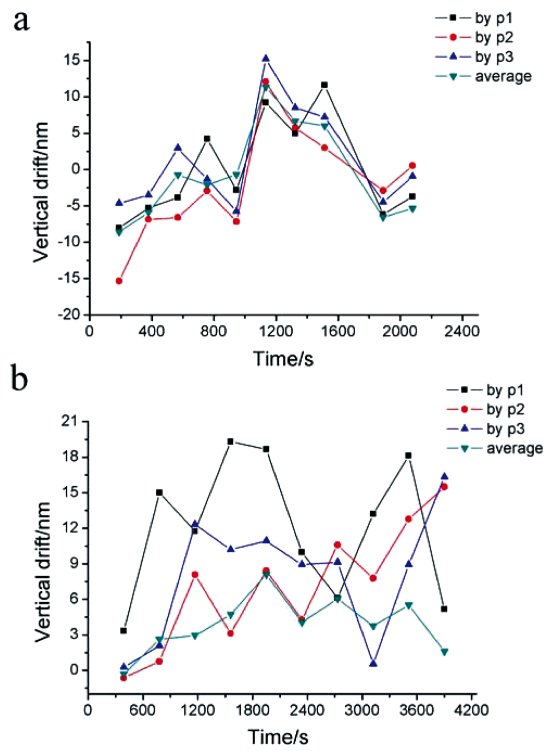

Fig. 5 Change of the average vertical drift and the vertical drifts calculated by feature points during consecutive scanning on Pt film (a) and periodic grating (b) as a function of time. It can be seen that there is no apparent trend of the vertical drift with time; also, the vertical drifts of the 4 groups of data are different from each other in each imaging. Noting that the vertical drift computed by the feature point is not simply the value of the corresponding point on the vertical drift image as in Fig. 3, see Ref. 18 for a detailed description of its calculation. Since one image was lost, there is one vacancy at time 1701 s in (a).

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18. Similar to the characteristic marker method for the lateral drift measurement,[11,12] first locating the position of the selected feature point on each image, then the heights at these positions in each topography image without any post-processing are recorded, set the feature point in the reference image as reference point, vertical drift on selected feature point could obtained from the height difference between the computing point and the reference point.