Cross-talk correction in atomic force microscopy

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(Received 6 October 2006; accepted 24 November 2006; published online 5 January 2007)

Commercial atomic force microscopes usually use a position-sensitive photodiode to detect the motion of the cantilever via laser beam deflection. This readout technique makes it possible to measure bending and torsion of the cantilever separately. A slight angle between the orientation of the photodiode and the plane of the readout laser beam, however, causes false signals in both readout channels. This cross-talk may lead to misinterpretation of the acquired data. We demonstrate this fault with images recorded in contact mode on periodically poled ferroelectric crystals and present a simple electronic circuit to compensate for it. This circuit can correct for cross-talk with a bandwidth of ~1 MHz suppressing the the false signal to ≪1%. *© 2007 American Institute of Physics.* [DOI: 10.1063/1.2424448]

The atomic force microscope (AFM) has become a standard tool for determining a variety of surface properties on the nanometer scale not only in physics but also in all life sciences. This is mainly due to its high versatility as it can detect frictional, electrostatic, or magnetic interactions between tip and sample.[1] This feature of the AFM is even more attractive since those interactions can be detected simultaneously. Unfortunately an unambiguous separation of the different readout channels is generally not assured. This results in cross-talk between the different channels. Although commercially available AFMs are equipped with a powerful software for operation and subsequent image processing, a correction for cross-talk is not provided. In this article, we address the problem of cross-talk between the readout channels for bending/buckling and torsion of the cantilever. Here we describe a simple electronic circuit to compensate for this cross-talk.

Figure 1 shows the notations used. The forces acting on the tip can be out of plane (1) and in plane (2) of the surface to be investigated. Whereas (1) leads to a bending of the cantilever, (2) results either in torsion or in buckling, depending on the direction of the force with respect to the axis of the cantilever. Note that bending and buckling lead to a "vertical signal," i.e., the movement of the cantilever is detected as $(A+B)-(C+D)$ at the position-sensitive detector, whereas torsion is seen as a "lateral signal" via $(A+D)-(B+C)$, where A, B, C, and D are the electrical signals from the four segments of the position-sensitive detector.

There are several reasons for cross-talk between the vertical and the lateral readout channel in AFM: (i) mechanical, (ii) electronic, and (iii) geometric (due to a misalignment of the optical detection system).[2–4] The first (i) generally arises when the tip mechanically hits an edge on the surface while scanning, thereby twisting the cantilever.[5–7] In some AFMs, the elongation of the tube scanner results in a change of the detection unit, thus, leading to false signals.[8,9] Finally, a mechanical coupling of the different motions of the cantilever can lead to cross-talk.[10] Mechanical cross-talk is, in particular, important when investigating samples with a pronounced topography. For reduction a low scanning speed together with a fast feedback loop is most appropriate. Note that on smooth sample surfaces mechanically caused cross-talk does not occur.

Concerning the cross-talk (ii) arising from electronics, a careful shielding of the signal wires seems most promising. This, however, can generally be assured by the manufacturer only, the user having no access to the electronics in the AFM head.

Geometric cross-talk (iii) is defined here as a misalignment of the optical detection unit. The adjustment of the readout laser beam consists of three steps: (1) adjustment of the laser beam on the back side of the cantilever, (2) centering of the backreflected laser beam on the position-sensitive detector (PSD), and finally (c) rotation of the PSD in order to minimize the angle α between the axis of the PSD and the plane of the laser beam (Fig. 2). This plane is given by the incoming laser beam and the beam reflected from the cantilever. Although the importance of PSD rotation is described in the literature,[2] an adjustment of the axis of the PSD in commercial AFMs is, in general, not possible and can only hardly by upgraded.[11]

In case of a misalignment by the angle α, the measured signals (V_m and L_m) can be obtained from the real vertical and lateral signals for bending and torsion (V and L) via the rotation matrix as

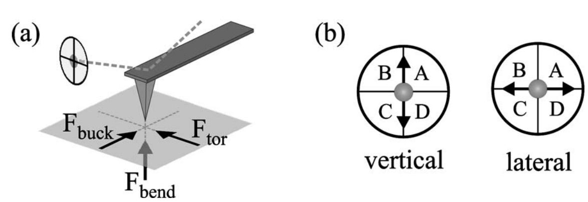

FIG. 1. (a) Forces acting on the tip. F_{bend}: forces out of the plane leading to bending of the cantilever, F_{buck} and F_{tor}: forces in the plane of the surface leading to buckling and torsion of the cantilever. (b) Readout with the position-sensitive detector, left: vertical signal (bending and buckling), right: lateral signal (torsion).

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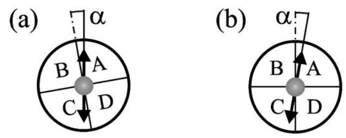

FIG. 2. Misalignment between the plane of the readout laser beam and the axis of the position-sensitive detector. A rotation of the photodiode (a) affects the readout in the same way as a rotation of the plane of the laser beam (b). Both cause an angular mismatch α that leads to false signals due to cross-talk between vertical and lateral signals.

$$\begin{bmatrix} V_m \\ L_m \end{bmatrix} = \begin{bmatrix} V \\ L \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix}. \quad (1)$$

The cross-talk-corrected signals V_c and L_c can thus be calculated by

$$\begin{bmatrix} V_c \\ L_c \end{bmatrix} = \begin{bmatrix} V_m \\ L_m \end{bmatrix} \begin{bmatrix} 1 & -x \\ x & 1 \end{bmatrix} = \frac{1}{\cos\alpha} \begin{bmatrix} V \\ L \end{bmatrix}, \quad (2)$$

with $x=\tan\alpha$. Note that the corrected signals become larger than the real signals. Therefore the calibration of output signals of the AFM has to be performed either after accomplishing the cross-talk correction or by the use of an adjustable voltage divider at the output.

To correct for this misalignment we designed an electronic circuit depicted in Fig. 3. This circuit adds to each readout channel a component from the other channel with the adequate phase and amplitude, adjustable with potentiometers. It was built with low-noise precision operational amplifiers (OP27) and applicable to frequencies $\lesssim 1$ MHz. This is generally enough for standard AFM applications.

In order to adjust the potentiometers P_V and P_L the determination of the cross-talk is required. This can be achieved by retracting the tip from the surface and exciting the cantilever at its resonance frequency (with the help of the piezo used for non-contact-mode operation). The spring constants and, accordingly, the resonance frequencies for bending and torsion of a cantilever are different, thus, using the adequate excitation frequency, the cantilever oscillates in its first bending mode only. In case of a perfect alignment of the optical detection unit $L_m=0$, i.e., no lateral signal is detected. Otherwise the potentiometer P_L has to be adjusted to obtain $L_m=0$. Since both channels suffer the same cross-talk, i.e., the same rotation α, P_V has to be set to the same value as P_L. Note that this procedure has to be repeated for every cantilever, and even for a new laser beam adjustment with the same cantilever.

To give an example of the efficiency of our electronic cross-talk compensator, we performed measurements on periodically poled lithium niobate (PPLN) crystals using a commercial AFM (SMENA fabricated by NT-MDT) in the piezoresponse mode.[12] Using PPLN as a test sample has the advantage that the thickness change of the crystal due to the converse piezoelectric effect is below 0.1 nm when applying 10 V to the tip. The width of the domain boundaries measured with the AFM, however, extends over a length scale of ~100 nm.[13] Thus any mechanical cross-talk can be neglected. The vertical signal is caused by the deformation of the sample, the lateral signal at the domain boundaries arises from electric fields generated by the surface polarization charges.[14] The left side of Fig. 4 shows simultaneously recorded deflection (a) and torsion (b) of the cantilever, without cross-talk correction. In (c) scan lines of these two images are presented. Obviously the domain faces are also visible in the lateral channel. Because the vertical signal has a much higher amplitude than the lateral signal, the reciprocal effect is not seen. When using cross-talk compensation (right side of Fig. 4) no contrast within the domains, but only the boundaries are visible.

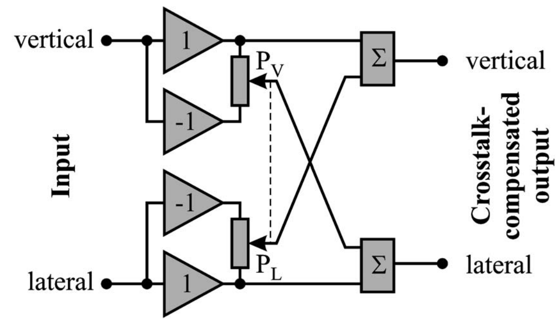

FIG. 3. Schematics of the electronic circuit used for cross-talk compensation. P_V and P_L: potentiometers for vertical and lateral cross-talk correction, respectively. Σ: summing of the signals.

A cross-talk compensation as presented above, could of course also be realized by a subsequent software processing of the recorded images. However, compared to the hardware solution proposed in this article, there are several drawbacks: (i) for the determination of the correction parameter (the angle α), a separate detection of the vertical and the lateral signal amplitudes (V_m and L_m) of the excited cantilever is required. Furthermore, their relative phase must be known to identify the sign of the necessary rotation. These signal parameters, however, are not accessible in general. (ii) For cross-talk compensation via software both images (lateral and vertical) are necessary since image processing takes only place after recording. (iii) This implies that a real-time monitoring of the data during image acquisition is not possible. (iv) Finally, a software-based solution limits the possibilities to record freely chosen input signals (e.g., the outputs of two lock-in amplifiers as demonstrated in the above presented example). Note that the drawbacks described above could be eliminated by the manufacturer with a software compensation during data acquisition and additional hardware modifications of the control unit.

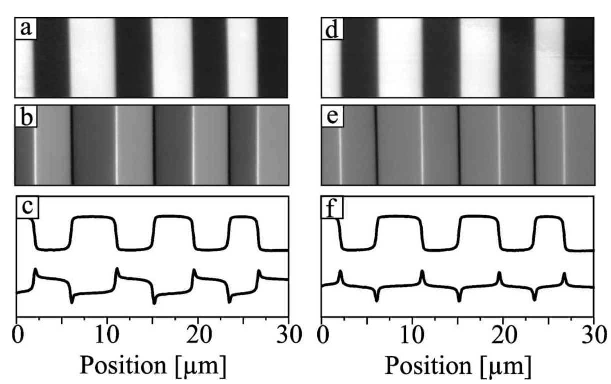

FIG. 4. Piezoresponse force microscopy images of periodically poled lithium niobate (PPLN). Left side with cross-talk and right side with compensated cross-talk [(a) and (d): vertical signal, (b) and (e): lateral signal, (c) and (f): appropriate scan lines]. The cantilever is orientated parallel to the PPLN stripes.

In this article we have demonstrated the effect of a misalignment of the optical detection unit on the recording of bending and torsion signals with AFM. We have furthermore proposed an electronic circuit to compensate for false signals caused by such a misalignment. This circuit can be incorporated into every AFM if the output signals of the position-sensitive detector are directly accessible.

Financial support of the DFG research unit 557 and of the Deutsche Telekom AG is gratefully acknowledged.

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