Increasing sensitivity while reducing crosstalk of the force sensor in atomic force microscopes

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Abstract

The sensitivity of the force sensor in an atomic force microscope (AFM) is an important property, as it is a determining factor for the vertical imaging resolution. While the angular sensitivity related to the real deflection of the cantilever should be as high as possible, the translational sensitivity should be minimized to reduce the crosstalk between the compensating cantilever movement and the deflection readout. This contribution analyses the angular and translational sensitivity and presents a novel design to significantly reduce the crosstalk while increasing the angular sensitivity by more than a factor of five.

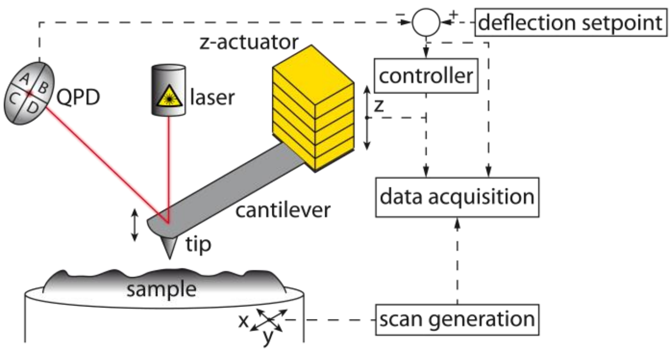

Figure 1: Schematic of an Atomic Force Microscope.

1. Introduction

The atomic force microscope (AFM) [1] is a very important tool for imaging, metrology, and manipulation of matter on the nanometer scale. The working principle of an AFM (Fig. 1) is to probe the surface of a sample by a sharp tip mounted on the free end of a micromechanical cantilever, while raster scanning the sample and tip relatively to each other. The cantilever with the integrated tip serves as the force sensor to probe the tip-sample interaction [2].

The deflection of the cantilever is usually monitored by an optical lever system [3][4], in which a laser beam is reflected off the backside of the cantilever onto a quadrant photodetector (QPD). In most AFM applications the highly nonlinear tip-sample interaction force is held constant via feedback operation, in order to avoid damage to the tip and the sample and to obtain reliable measurement data. The output of the feedback controller corresponds to the displacement required to maintain a constant imaging force, thereby converting the force measurement into a displacement measurement with well known characteristics of the actuator.

If the interacting force is held constant by displacing the cantilever, the relative position of the cantilever with respect to the QPD changes, leading to a crosstalk between the displacement and the deflection signal and resulting in undesired force variations.

2. Sensitivity and Crosstalk

With the assumptions from [2] the static deflection Δz_{defl} of the free end of the cantilever causes a deflection $\Delta d = 3(s/l)\Delta z_{defl}$ on the QPD, where l is the cantilever length and s is the distance between the cantilever and the QPD.

Although the deflection of the laser spot is proportional to s (geometrical amplification) the measured deflection signal depends also on the spot size of the laser beam on the QPD. As the laser beam is usually focused on the back of the cantilever with a spot size D_0, the reflected beam is diverging over the distance s. If the distance s is much longer than $\pi D_0^2/4\lambda$ with the wavelength λ, the beam diameter and the displacement of the laser spot on the QPD are both proportional to s and the SNR is diffraction limited [5].

Fig. 2a shows that a compensating movement of the cantilever involves a parallel shift of the laser beam leading to a false deflection signal at the QPD. As the feedback compensates the misinterpreted part of the deflection signal too, the tip sample interaction force may vary. The equivalent cantilever deflection as a function of the compensating cantilever movement can be expressed as $\Delta z_{defl}=[l \sin(2\alpha)/3s]\, \Delta z$.

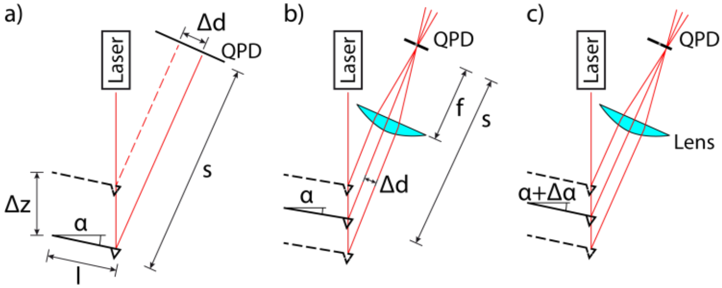

Figure 2: Crosstalk due to compensating cantilever movement (a) compensated by an additional lens (b) while preserving the sensitivity (c) to a tilt of the cantilever.

3. Additional lens in the optical path

To overcome the aforementioned diffraction limited SNR a lens in the optical path of the AFM can be used to focus the deflected laser beam onto the QPD, as shown in Fig. 2b and c. Additionally, as the origin of the crosstalk is a parallel shift of the laser beam, the basic property of an ideal lens, that it is focusing parallel rays to a single point in the focal plane, can be utilized to compensate for the crosstalk. Fig. 2 shows that a change in the tilt of the cantilever due to a force on the AFM tip still leads to a deflection on the QPD while the parallel shift due to the compensation movement of the cantilever is no more visible on the QPD.

To test the crosstalk reduction capability a laser source with a distance of s=190 mm to the QPD is shifted by a linear stage perpendicular to the laser axis while recording the displacement signal of the QPD. As it is not possible to perform a pure parallel shift with the used linear stage, two additional capacitive sensors are added to the setup to measure the displacement at the front and back end of the laser source to allow the calculation of the tilt α and the average displacement x.

The measured deflection signal $U_{defl}(t)$ can be modeled as a linear combination $U_{defl}(t) = \alpha(t)\, k_{tilt} + x(t)\, k_{shift}$, with k_{tilt} and k_{shift} as the sensitivity to the tilt and shift, respectively. If $\alpha(t) \neq cx(t)$ for any constant c, k_{tilt} and k_{shift} can be found by fitting the model function $U_{defl}(t)$ to the measurement data. Without a focusing lens between the laser source and the QPD the measurement and separation of the shift and tilt components leads to k_{shift}=5.592·10^4 V/m and k_{tilt}=2.042·10^2 V/°.

4. Results

In Fig. 3 the values of k_{shift} and k_{tilt} are plotted with respect to the displacement of the focusing lens (Thorlabs LBF254-040-A, f=40 mm) from its optimal position. To show the repeatability and long term stability five spatial sweeps with 64 records each are acquired with a temporal separation of at least 20 hours.

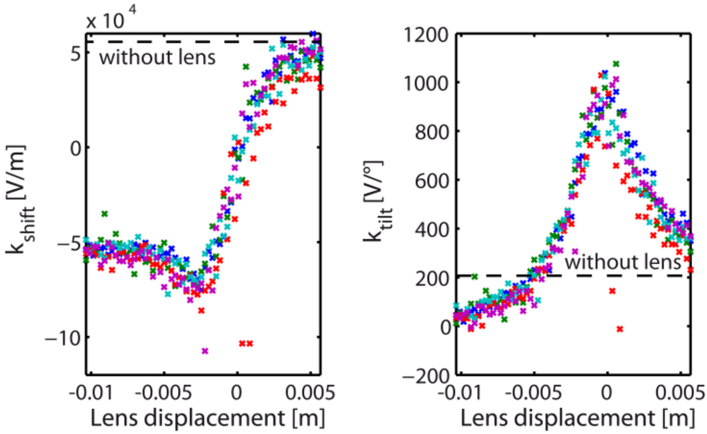

Figure 3: Measurement results for the crosstalk and the sensitivity with respect to the displacement of the focusing lens from its optimal position.

From Fig. 3 it can be seen that there is an optimal alignment for the additional focusing lens increasing the sensitivity of the deflection measurement by a factor of five while significantly reducing the crosstalk between the z-actuation and the deflection measurement. In a next step the resolution enhancement and cross-talk reduction due to the additional focusing lens will be evaluated in an actual AFM system at real imaging experiments.

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