Novel Three-Dimensional Beam Tracking System for Stationary-Sample Type Atomic Force Microscopy

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Abstract – The stationary-sample type atomic force microscope (AFM) has been demonstrated to have many advantages over conventional scanning-sample type AFM. However, a higher degree of instrumentation complexity has to be adopted to measure the deflection of a 3-dimensional moving probe in the stationary-sample type AFM. This paper proposes a novel stationary-sample type AFM with a laser beam tracking system. We devise an innovative method to minimize "false deflection". Our system has been verified to achieve high scanning speed without sacrificing high accuracy.

Keywords– atomic force microscope (AFM), optical instrumentation

I. INTRODUCTION

AFM [1] can produce 3-dimensional images of a surface with nanometer resolution. Usually, the samples scanned while the AFM probe is kept stationary (scanning-sample type AFM). However, problems arise for some occasions. For example, large sample or heavy samples, such as semiconductor wafer. Temperature control (heating or cooling) of the sample may also affect the performance of the PZT scanner, which is might below the sample. For samples (such as bio molecules) in a liquid cell, scanning-sample type AFM may also cause some problems.

The stationary-sample type AFM, in which the probe is scanned while the sample is kept stationary, has been adopted to solve the above problems. One way to achieve this is to let the whole optical detecting system move with the probe. However, the optical detecting set, including the laser diode (LD), the position sensitive detector (PSD), alignment mechanisms and the frame structure for maintaining the optical configuration, is often too massive to move with the scanner. Some methods have been proposed to reduce the total mass of the moving parts. The tracking lens method [2] is a typical solution to deal with this problem. In that design, however, the tracking error can limit its resolution. For an ideal optical tracking, when the laser beam emitted from the stationary LD perfectly tracks the moving probe, the signal picked up by the PSD depends only on the deflection of the probe but not on the scanning motion. If the PSD signal changes during scanning while deflection of the probe is null, such situation is called false deflection or optical tracking error.

To reduce false deflection, a 1-dimensional beam tracking method that makes the PSD move synchronously with the probe was introduced [3]. Hansma and Drake proposed another method that sets up a convex lens before PSD to reduce false deflection [4]. In their system, however, the tracking function applies to the horizontal directions but not the vertical direction. On the other hand, the tracking function was designed only for the tube type scanner but not the flexure type scanner. A 3-dimensional beam tracking system by tracking mirrors was later proposed by Nakano [5]. In that system, the working distance from LD to the reflection point of the probe changes during scanning. That means the intensity signal of the beam varies if some portion of the beam falls off the probe due to defocus of the laser spot on the probe. If it occurs, the shape of the reflected beam will be warped on the PSD and the PSD position signal will be adversely affected also. A special type of twist-probe was used. It has large mirror portion and can reduce the fall-off, but its installation will readily limit one dimension of the image size. Another disadvantage of the twist-probe is its distance to the PSD may change during scanning so that the constant relation between probe deformation and the PSD signal cannot be guaranteed.

The objective of this paper is to develop a new three-dimensional beam tracking AFM system applicable to the flexure type scanners and the case of widely used bending mode probes. The aim is to limit both vertical and horizontal tracking errors to be limited <0.3nm over 4μm scanning distance and to <12nm over 100μm scanning distance.

II. PROBLEM DEFINITION

In the conventional scanning-sample type AFM, the 3-dimensional motion of sample is carried out by a PZT scanner. The motions consist of a raster horizontal scanning motion in X-Y plane and a fast vertical tracking motion in the Z axis. The stationary probe and its optical-lever mechanism generate a signal, which depends only on the probe's deflection caused by the force field between the tip and the sample. This signal is fed into a controller so as to form a feedback loop forcing the sample up and down in order to keep the tip-sample gap constant. Then, we can obtain the sample's profile because it matches the scanner's trajectory.

In the stationary-sample type AFM, the PZT scanner carries the probe to move and the sample is completely fixed. Despite that this kind of configuration provides advantages, "false deflection" should be prevented. The key point of the design is that the signal transduced from PSD should only depend on the cantilever's deflection but not on the scanning motion. If the scanning motion may influence this signal, this undesirable side-effect is then called false deflection or tracking error.

There are two major challenges in the instrumentation of optical-lever based stationary-sample type AFM. The first one is to let the focused laser spot track an invariant point on the probe's cantilever, which is moving 3-dimensionally during scanning. While sample is far away from the probe and induces no deflection, how to let the laser beam, which is reflected from the moving cantilever, hit an invariant point (e.g. the center) of the PSD is the second challenge. The goal of this paper is to develop a novel stationary-sample type AFM that satisfies the two conditions above while limiting the false deflection.

III. LASER BEAM TRACKING SYSTEM

A. Vertical tracking

The proposed beam tracking system is shown in Fig. 1, where the probe is installed at the focus of the objective lens. The relative position of the probe and the objective lens is maintained by the aluminum made lens holder, which is attached to the bottom of the Z scanner. The collimated beam, emitted by the LD and then adjusted by a 4-axis laser mount, is kept parallel to the up-and-down motion of the Z scanner. The reflected beam from the probe is collimated by the same objective lens and then adjusted by mirrors #1, #2, and #3 to aim at the center of the PSD. The optical configuration will remain invariant during Z motion, and hence the tracking function is exactly achieved by the synchronized objective lens. In addition, a piezo oscillator is used to perform tapping mode of AFM.

There should be no vertical tracking error theoretically. However, it is not eliminated because the imperfection of optical elements and mechanical mis-alignment. The experimental result of vertical tracking error is shown in Fig. 3. It is less than 0.3nm for Z motion over 4 μ m. The testing procedure is stated below. The Z scanner is driven to move periodically in amplitude z_p and frequency ω . The sample is kept far away from the probe so that there should be no interaction force can induce deflection. Any measured deflection is caused by the false deflection. A sensitive lock-in amplifier is used to detect the small false deflection by locking the frequency at ω .

Fig. 1. Schematic diagram for the proposed system.

1: laser diode	2: collimation lens
3: polarizer	4: beam splitter
5: $1/4 \lambda$ wave plate	6: objective lens
7: correction lens	8: Z tube-scanner
9: moving part of the horizontal scanner	
10: fixed part of the horizontal scanner	
11: flexure guiding system	12, 13, 14: mirror #1-#3
15: 4-segmented PSD	16: approach mechanism
17: piezo oscillator	18: lens holder
19: probe	20: sample
21: vibration isolator	

Fig. 2. Optical configuration during X scanning.

Fig. 3. Vertical tracking error.

B. Horizontal tracking

During X or Y scanning, the changes of the optical configuration are shown in Fig. 2. When the probe shifts by a distance x_p , the incoming beam and the reflected beam do not remain coaxial. The distance between their centers is called beam shift, denoted as x_B , which is roughly twice of x_p . The exact optical configuration around the probe is shown in Fig. 4, where θ_c is the tilt angle of the probe to guarantee the lowest point of the probe is the tip. Generally speaking, $10^\circ \sim 15^\circ$ is feasible, and hence 12° is chosen in the present design. Moreover, f is the focal length of the objective lens, which is 9mm, with R denoting the origin making incoming and reflected beam coaxial. Correspondingly, the reflected beam moves from P to P' (x_B) when the probe moves from R to R' (x_p). The mathematical relation between x_B and x_p is described in (1). A plot is shown in Fig. 5.

Fig. 4. Optical configuration around the probe.

If the displacement of the laser beam and that of the probe were equal (i.e. $x_B = x_p$), the correction lens would not be needed. The synchronized PSD motion could eliminate the false deflection automatically. However, x_B is roughly twice of x_p . Fortunately, the relation between them is

approximately linear. Taking horizontal scanning range to be $100\mu\text{m}$ and mechanical mis-assembly x_θ to be 1mm (i.e. x_p travels from 0.95mm to 1.05mm), we can use linear approximation (2) instead of (1). The linear compensation is realized by installing the correction lens at a distance of f_c / C above the PSD, where f_c is the focal length of the correction lens.

$$x_B(x_p) = \sqrt{f^2 + (x_p - f \tan \theta_c)^2} \cdot \frac{\sin(2\theta_R(x_p))}{\sin(\theta_p(x_p))} \quad (1)$$

$$\text{where } \theta_R(x_p) = \theta_c + \tan^{-1}\left(\frac{x_p}{f} - \tan \theta_c\right)$$

$$\theta_p(x_p) = \frac{\pi}{2} - 2\theta_c - \tan^{-1}\left(\frac{x_p}{f} - \tan \theta_c\right)$$

$$x'_B(x_p) = Cx_p + x_B(x_0) \quad (2)$$

Fig. 5. Approximate linear behavior between x_p and x_B .

The relation between probe deflection v_p and laser beam shift x_B is shown in Fig. 6. and described in (3), where L is the length of the cantilever of the probe and is chosen to be 0.45mm . Optical-lever effect can be described by this equation. The difference between x_B and x'_B is the approximation error Δx_B , which is transformed to false deflection by (3). The horizontal false deflection resulting from the current set-up is shown in Fig. 7. It is 12nm over $100\mu\text{m}$ scanning distance. The measured data are a little bit greater than the estimated values. Besides the imperfection of the optical elements and mechanical mis-assembly, the out-of-plane motion of the X-Y scanner may be the dominant reason. Fortunately, this kind of error is a deterministic function of the X-Y scanner's location. We can measure it off-line and then subtract it from every acquired image in order to minimize this error effect. We did not perform this compensation. In the following test, which captures a $11\mu\text{m} \times 11\mu\text{m}$ region around the corrected point. In this small region, the tracking error is comparable to the background

noise and hence is negligible. It is mentioned that the correction lens should be installed at a particular location. Mis-installation will induce greater tracking error, which is shown in Fig. 8. The location of the correction lens is fine tuned by a translation table. After appropriate adjustment, the minimized tracking error can be obtained.

$$\Delta v_p \approx \frac{L}{3f} \Delta x_B \quad (3)$$

Fig. 6. Optical-lever effect to detect the deflection of the cantilever.

Fig. 7. Horizontal tracking error.

Fig. 8. Tracking error induced by mis-installation of the correction lens.

IV. TEST RESULT

Figure 9. shows the experimental setup for testing. Besides the proposed stationary-sample system, we place an additional independent scanner (secondary scanner) under the sample. We can switch the driving voltages from the primary scanner to the secondary scanner to compare the performance of the proposed system and that of the conventional scanning-sample type AFM. We choose the same type of PZT tubes ($4\mu\text{m}/400\text{V}$) for both the primary and secondary scanners.

Fig. 9. Photograph of the experimental setup.

A commercial AFM controller (Digital InstrumentTM NanoScape[®] IIIa) provides a signal access module, which is used to drive our hardware. The specimen is a standard grating with a step height of $26 \pm 1 \text{ nm}$ and the horizontal pitch length of $3 \pm 0.1 \mu\text{m}$. This specimen is attached on a 51g brass block, which is used to simulate a heavy sample. The vertical working frequency of the secondary scanner can be expected to lower due to greater mass it carries. In comparison, the mass carried by the primary Z scanner is only 3g. The following experimental results demonstrate the performance of our method. Two images, Fig. 10(a) and (b), taken with different scanning speeds clearly indicate that the secondary Z scanner cannot follow the fast change of the surface topograph and induce distortion in the height profile. In contrast, the proposed stationary-sample type AFM system performs well without image distortion even at high scanning speed (Fig. 10(c) and (d)).

Fig. 9. AFM topographs and height profiles of a standard grating
 (a) Conventional method, 5 $\mu\text{m/s}$ in a horizontal direction
 (b) Conventional method, 50 $\mu\text{m/s}$ in a horizontal direction
 (c) Proposed method, 5 $\mu\text{m/s}$ in a horizontal direction
 (d) Proposed method, 50 $\mu\text{m/s}$ in a horizontal direction

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