A large-stage atomic force microscope for nondestructive characterization of optical thin films

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A novel large-stage atomic force microscope (AFM) for nondestructive characterization of optical thin films is built. An open sample stage and a probe unit are employed to measure samples with large size and weight. Three optical thin films with large areas are imaged using this AFM without needing to cut the pieces apart. Experimental results show that the maximum scanning range for one single image can reach 20×20 (μm) while keeping a high resolution laterally and vertically. The maximum possible size of a sample is 600×1000 (mm). The new AFM is capable of performing wide-range and high-resolution characterizations of large samples such as large-area optical thin films.

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The atomic force microscope (AFM) is a powerful instrument used to measure nanometer-scale topography of sample surfaces. Since its invention in 1986 by Binning *et al.*, the AFM has evolved significantly through efforts in refining its capabilities and conveniences[1]. In the conventional design of an AFM[2,3], the cantilever tip is stationary and the sample moves. This kind of design is impractical for large samples such as silicon wafers and optical thin films with large areas[4−7]. Some conventional scanned-cantilever AFMs[8−12] are then designed in an attempt to image large samples. One problem is that these conventional AFMs only have good performance in a small scanning range due to the relative shift between the laser beam and the cantilever. As an alternative approach, we present the development of a novel scanned-cantilever, large-stage AFM. With some special designs, the new AFM is able to perform wide-range and high-resolution characterizations of large samples such as large-area optical thin films.

The setup of a large-stage AFM system is shown in Fig. 1. The open sample stage enables nondestructive detection of large and heavy samples, such as large-area optical thin films. A rigid architecture is fixed on the worktable to enable it to carry a motorized translation stage with a maximum travel distance of 300 mm. The probe unit is installed on the motorized translation stage to enable back and forth movement in the X direction under the control of a step motor (MTS123, Beijing Optics Center Instruments Inc., China) (Fig. 1(a)). Another motorized translation stage with the same maximum travel distance is fixed on the worktable to carry an open sample stage. Thus, the stage can be translated back and forth in the y direction using this motorized translation stage, which is controlled by another step motor (Fig. 1(b)). The open sample stage has an area of 600×1000 (mm), on which large and heavy samples can be placed and measured.

Therefore, the probe unit can be located at any position on the sample surface by moving the two motorized translation stages. Unlike conventional AFM, which can only be used to scan small samples, the new AFM is able to measure samples as large as 600×1000 (mm) without needing to cut the pieces apart.

Since the cantilever scans while the laser diode (LD) is fixed, the laser beam does not perfectly follow the cantilever during scanning. Relative motion of the focused spot and the cantilever would limit the scanning range or decrease the deflection sensitivity. The solution is to find an optical path that allows the focused spot to track the cantilever during its motion. Therefore, a beam tracking optical path is further employed in the new AFM (Fig. 2). Three perpendicular piezoelectric tubes constitute a scanner for xy scanning and z feedback control. In order to perform tracking between the

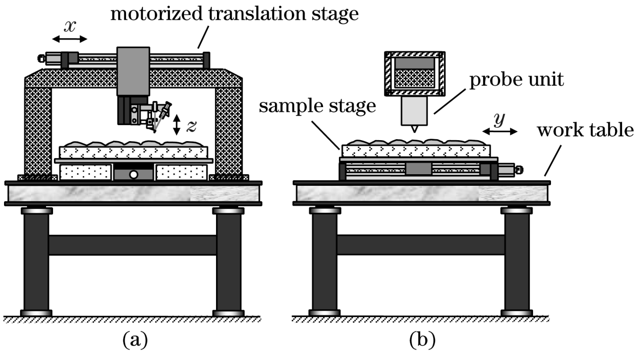

Fig. 1. Setup of the large-stage AFM system. (a) Front view, (b) side view.

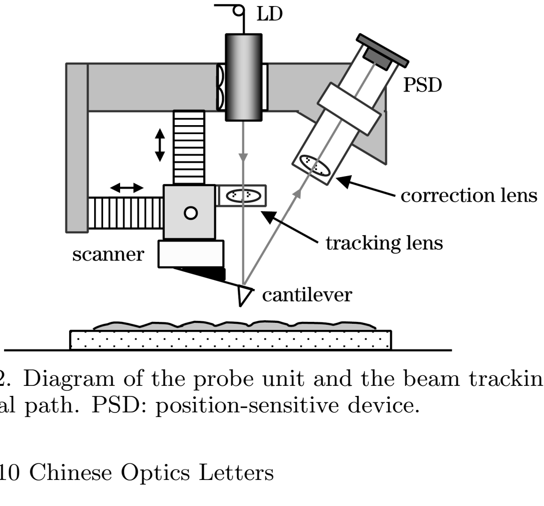

Fig. 2. Diagram of the probe unit and the beam tracking the optical path. PSD: position-sensitive device.

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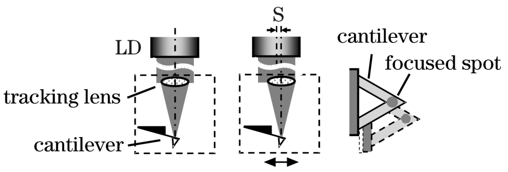

Fig. 3. Principle of beam tracking by using a tracking lens.

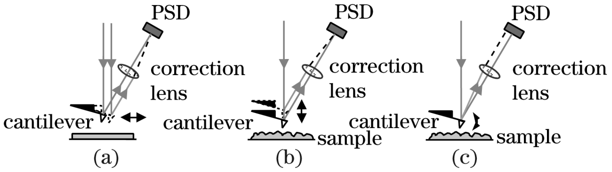

Fig. 4. Schemes of the optical path using the correction lens (a) during scanning without sample, (b) during feedback, and (c) when the cantilever deflects.

laser spot and the cantilever, a tracking lens is attached to the scanner with its optical axis parallel to the axis of the LD. The cantilever is assembled at the focal point of the lens.

Since the end of cantilever is located at the focal point of the tracking lens, the parallel beam from the LD passes though the tracking lens and forms a focused spot on the back of the cantilever. Both the cantilever and the tracking lens are attached to the scanner to keep them relatively stationary. During scanning, the focused spot accurately tracks the lateral movement of the cantilever (Fig. 3).

Since the position-sensitive device (PSD) is stationary (see Fig. 2), it will not move with the scanner during scanning. Therefore, even if the cantilever does not actually deflect, the reflected laser from the back of cantilever will move with respect to the fixed PSD during scanning. This false deflection signals might produce spurious information in the image of the samples. In order to solve this problem, a correction lens is fixed in the focusing plane of the PSD (Fig. 2) to eliminate false deflection signals. The situation during scanning without sample is shown in Fig. 4(a). Since the PSD is located at the focal point of the correction lens, parallel beams converge to a spot on the PSD when the cantilever moves horizontally without bending. Thus, false probe deflection can be eliminated completely. The situation when feedback is introduced is shown in Fig. 4(b). Relative movement between PSD and cantilever usually leads to false probe reflection signals, which is why the scan range is usually small in the z direction. The newly designed AFM in this letter solves this problem. The parallel movement of the laser can be eliminated by using the correction lens when the cantilever moves vertically without deflecting. Therefore, the AFM can work efficiently with this special design even when the feedback is significant. The situation when the cantilever is actually deflecting is shown in Fig. 4(c). In this case, the reflected beam changes its direction, resulting in a displacement of the laser spot on the PSD surface. This displacement is not affected by the correction lens; therefore, it can be recorded by the PSD to obtain images of sample surfaces.

With this beam tracking optical path, the AFM system can perform wide-range scanning and large-scale feedback with high accuracy. In order to further increase the scanning range, image splicing is applied. Test samples can be placed on the open sample stage, which is translated by the step motors. Whenever the sample is moved a certain distance, an AFM image can be acquired by the scanner. Thus, a series of sample images can be obtained by the scanner with the help of the step motors. According to the corresponding relationship between adjacent images, sample images with wider range can be acquired by splicing the sequential images together.

Experiments were carried out to determine the characteristics of the new AFM. We choose a 10-mW LD as the light source (wavelength $\lambda = 650$ nm). Each cantilevers (seiko Instruments Inc., Japan) had a length of 100 or 200 μm with a pyramid tip of 10-nm curvature radius. Gold-plated films with 2-dimensional (2D) microstructure, 2D grids and Ge quantum dots served as the test samples. The experimental results were taken in the air and at room temperature of approximately 23°C.

The image of a gold-plated film with 2D microstructure is shown in Fig. 5. The scanning range is 20×20 (μm). This kind of gold-plated film is usually too large and heavy to be characterized by conventional AFMs. However, it can conveniently be measured by this large-stage AFM without needing to be cut into smaller pieces.

The large-range image of 2D grids with a size of 68×20 (μm) is shown in Fig. 6. It was obtained by splicing four sequential images together. Each of the images had a scanning range of 20×20 (μm). After the first scanning image was acquired by the scanner, the sample was moved for about 16 μm by step motor. The second scanning image was then acquired by the scanner. The size of overlap between the two images is 4×20 (μm). In this way, a series of sample images were acquired and then stitched together into a single image with wider range (68×20 (μm)). The range of scanned images can reach scales in the order of millimeter using this method.

The AFM image of Ge quantum dots grown on Si substrate, with a scanning range of 4×4 (μm), is shown in Fig. 7. Ge quantum dots can clearly be observed from this image, showing that the AFM has high resolution both laterally and vertically.

According to the results, the new AFM is suitable for the measurement of large and heavy samples. It can also

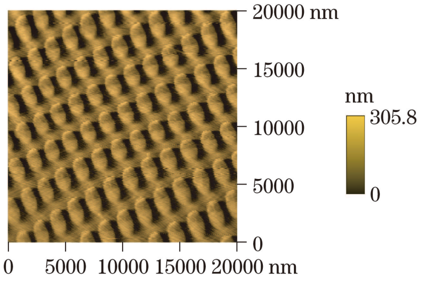

Fig. 5. Image of gold-plated film with 2D microstructure, the scanning range is 20×20 (μm).

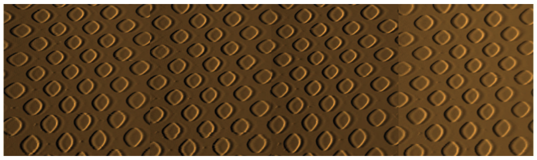

Fig. 6. The large-range image of 2D grids formed by splicing four sequential images together. The total size is 68 μm.

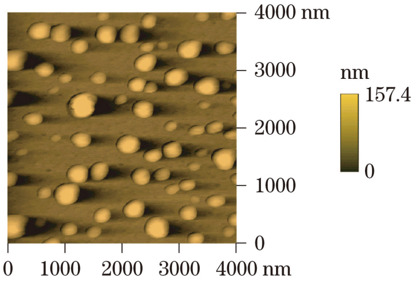

Fig. 7. Image of Ge quantum dots with a scanning range of 4×4 (μm).

give good performance in a large scanning range. The characteristics of the AFM, such as the resolution, repeatability, and contrast, can satisfy the requirements of measuring optical thin films in a nanometer scale.

In conclusion, a novel large-stage AFM is designed and applied for nondestructive characterization of optical thin films. An open sample stage and two step motors are employed in driving the probe unit and characterizing different areas of large samples. The size of sample can reach up to 600 × 1000 (mm). In practical applications, it is suitable for the measurement of large-sized optical thin films without cutting the pieces apart. With a beam tracking optical path, the new AFM can perform xy scanning and z feedback control in a large range. Experiments show that the scanning range for a single image can reach 20 × 20 (μm). By splicing the sequential images together, an image with a 68 × 20 (μm) scanning range is obtained while still maintaining a high resolution. In fact, the scanning range can be further enlarged to a scale on the order of millimeter. It is an ideal and practical tool for characterizing large-area optical thin films with high resolution in a wide scanning range.

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