A Dual Probes AFM System with Effective Tilting Angles to Achieve High-Precision Scanning

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Abstract— With the constant improvement of micro-fabrication techniques, the measurement of feature size of micro-fabricated structures becomes an important issue. Atomic force microscopy (AFM) is a high accuracy measurement instrument which has been widely used in micro-fabricated structures measurement recently. However, due to the monotonic tilting angle of the probe in traditional AFM system, the scanning results of sample with high steep wall feature usually have distortion phenomenon at the corner part of the sample. To solve this problem, a novel dual probe AFM system is proposed in this paper. A system structure with high flexibility is used in this work to create different tilting angle of each probe. With the tilting angle deciding method developed in this paper, we can estimate the effective tilting angles for scanning under different scenarios. In addition, a useful merging method is also designed in this work, which can stich result from different scanning unit together and produce high-precision scanning results. Experimental results are shown to validate the outstanding capability of the proposed system and methods.

Index Terms—Atomic force microscopy (AFM), dual-probe AFM, merging method, tilting angle, high-precision scanning

I. INTRODUCTION

WITH the improvement of micro-fabrication techniques, the feature size of micro-fabricated structures continuously shrink. For most of these structures, they are with high aspect ratio and steep side wall [1], and their qualities have a lot to do with their featured parameters such as width, height or sidewall angle. Accordingly, accurate measurement of micro-fabricated structures has become one of the most important tasks in metrology. Since scanning probe microscope (SPM) was invented in 1982 [2], it has been an important tool to measure the sample in nano scale. However, for its scanning principle, it can only be used to measure conductive sample. To overcome this restriction, Binnig et al. proposed atomic force microscope (AFM) in 1986 [3], AFM can be used to scan both conductive and insulating samples in nano scale and provide super-high image resolution. Nowadays, AFM has become one of the most crucial measurement instruments, and it has been widely used in different fields [4, 5]. AFM has also been used for micro-fabricated structure measurement. Typically, the scan result is obtained by recording the moving trajectory of the probe which will have different behavior when the distance between probe and sample changes. Because of the top-down set up of traditional AFM, the probe can only sense the variation parallel to probe’s moving direction, due to this limitation, it can’t sense the profile on the sidewall of sample. In other words, it’s hard to reconstruct the correct topography of sample with steep sidewall using traditional AFM [6].

For the past few years, a lot of studies try to overcome this limitation of AFM from different respects. For example, Liu et al.[7] designed a “T-shaped” probe which can easily scan the sidewall of sample. Ju et al. [8] proposed a scanning system with a tilting stage that can rotate the sample to change the probe-sample relative angle thus eliminating the scanning blind region near the sidewall of the sample. Hua et al. [9] designed a novel 3-Dimensional AFM, which is capable of tilting the tip before every scanning, and this kind of design can fully access the sidewall corner of sample to reconstruct a correct scan result. Fouchier et al. [10] developed a line edge roughness measurement technique by tilted sample at 45°.

In this work, a novel dual probe AFM system capable of high accuracy measurement is proposed, with mechanism designed, it is capable for tilting each probe with different angle. To fully utilize the advantages of this new system, we proposed a high accuracy scanning method. By scanning the sample with different tilting angle and opposite trajectory for each probe, we can capture different features on the samples from each probe, thus eliminating the scanning error causing by monotonic probe-sample angle in traditional AFM system. With the new algorithm we proposed in this work, we can properly merge the scanning result acquired by different probe together and generate correct scanning image. In addition, to determine the tilt angle we need in each probe, we also formulated the relationship between the probe and sample, and derived criteria to calculate the proper tilting angles for each probe. With the new criteria, we can get a range of available tilting angle which guarantees the scanning accuracy.

This paper is structured as follows. Section II introduces the system design for this work. Section III describes the details of proposed high accuracy scanning method which includes the tilting angles deciding mechanism, and the scanning results merging method. Section IV presents the experimental results and the conclusions of this paper are given in Section V.

II. SYSTEM DESIGN

The overall schematic diagram of the dual probe AFM system is shown in Fig. 1. The system can be divided into three parts, first part is the scanning unit, which is responsible for moving the measuring unit in three axes. Another one is the measuring unit which takes care of sensing the surface profile of the samples. Finally, an alignment unit is designed for precisely tuning the mutual position of dual probe. The features of each part will be detailed in the following subsections.
A. Scanning Unit

The detail structure of scanning unit is shown in Fig. 1(a). Because of the dual probe structure, here are two separate scanning units with almost the same architecture. Scanning unit $I$ is composed of a set of linear stages, a connecting mechanism, and a three axes piezoelectric scanner. The linear stages are set to adjust the horizontal distance between two scanning units and tune the relative height of the scanning units. The three axes piezoelectric scanner consists of a $z$-scanner and a $xy$-scanner. The $z$-scanner is a commercial $z$-piezostage (Piezosystem Jena PZ 38 SG T-102-00), which has the motion range of 38 $\mu$m. The $xy$-scanner is also a commercial two axes piezostage (Piezosystem Jena PX 38 SG T-101-01) with travel range of 32 $\mu$m in each axis and embedded strain-gauge sensor.

Scanning unit $II$ has almost the same configuration as the first one while replacing the three axes piezo-electric scanner by a commercial three axes piezostage (Piezosystem Jena PXYZ 100 SG T-101-01) with 80 $\mu$m travel range in each axis and embedded strain-gauge sensor. There are two main tasks for the scanning unit, First is to carry the measuring unit and move along the assigned scanning trajectory. The second task is to adjust the height of the measuring unit in desired location based on the feedback information of the probe during the scanning process. Here, unlike the traditional AFM system, we chose to move the measuring part instead of sample to create higher flexibility for dual probe structure.

B. Measuring Unit

Our AFM system is tapping mode operation by amplitude modulation, which has the advantage of higher sensing resolution and causing less damage to the sample. Unlike normal AFM system, here we chose to use a self-sensing and self-actuating probe, Akiyama-Probe, it does not require a laser to sense the amplitude of the probe. By combining its cantilever with a quartz tuning fork, the amplitude of the oscillating probe can be obtained by Akiyama-Probe [11] and lock-in amplifier. To generate the vibration required for the probe under tapping motion, we utilize a function generator which provides a sinusoidal waveform with the frequency near the first resonant frequency of the probe to the tuning fork. In this work, we chose the Akiyama-Probe to eliminate the optical path problems for simply dual probe architecture. The schematic diagram of the measuring unit is shown in Fig. 1(b).

To create the tilting angle of the probe is needed in this work, here we used a fixed angle connector (The tilting angle will be decided by the method in Section III).

C. Alignment Unit

Another problem we have to solve in measuring part is the alignment problem of these two probes. If we scan the sample without aligning the probe to each other precisely, we will get information from different area for the sample while taking them as the same. This miss alignment will make the scanning result distort and influence the precision of the scanning image.

In this work, we implemented an optical microscope, which was set above the sample and probes. The maximum working range of the optical microscope is 35 mm, and the maximum magnification ratio is 1840. A CCD camera is also attached on the microscope to take a picture of probes. With the picture get from microscope, we can roughly adjust the relative position of these two probes. However, the optical microscope can only provide micro-meter level information, which is not sufficient in our application. To totally eliminate the alignment error, we proposed a calibration method, which can guarantee the initial position of each probe will align to each other precisely. First, we will use the optical microscope to adjust the position of each probe coarsely. After the rough tuning, we will approach the probes toward a square standard grating from vertical direction, as shown in Fig. 2. When the amplitude of the probe starts to decrease because it comes near the sample, fix the probe and stop the approaching movement. After each of the probes achieves this situation, the height of two probes are set to the same level.

The next step is to align two probes in horizontal surface. Similarly, we move the two probes toward the same direction horizontally, and because of what we have done in the previous step, the amplitude of the probe is smaller than which at free oscillation, but as soon as the probe leave the bulge region, it will turn back to free oscillation immediately. Fix the probe at the corner point. After two of the probe stop at the corner point, as shown in Fig. 3, we can make sure that these two probes are aligned correctly in horizontal direction. With the method we proposed, it’s easy to align two probes to each
other precisely, and the whole calibration can be done within 10 seconds.

![Fig. 2 Vertical alignment configuration of dual probes](image)

![Fig. 3 Horizontal alignment configuration of dual probes](image)

III. SCANNING METHOD

A. Tilting Angles Deciding Mechanism

To fully utilize the advantages of probes with tilting feature, in this work, we design a tilting angles deciding mechanism, it can give a range of available tilting angles which can make sure the accessibility of probe to corner and side area of the samples. During the scanning process, the tip will come into contact with the side of the sample, the geometric diagram is as shown in Fig. 4 Here, we modeled our tip as a triangular shape with half-apex angle of $\alpha$ and the tip length is $\ell$, and the turning angle of the probe is $\beta$. For the model of sample, we assumed that the side wall angle is $\sigma$ and the height of the sample is $h$. To derive the relationship between tilting angle and scanning performance, our hypothesis is that the scanning performance should be correlated with the angle between probe and sample, which is annotated as $\psi$ is the figure. The smaller the $\psi$ is, the better performance we can get during the scanning. We can change $\psi$ by adjusting the tilting angle $\phi$ of the probe, if $\psi \leq 0$, we can make sure that the apex of the probe can access to the corner part of the sample, based on this condition, we can derive the following design rule:

$$\phi \geq \sigma + \alpha + \beta - \pi$$  \hspace{1cm} (1)

However, there is another constraint we have to consider when designing the tilting angle. When we’re trying to scan the sample with repeated pattern, if we choose a large tilting angle, the tip will hit the adjacent pattern before accessing the corner of the sample. If the pitch between two patterns is $p$, we can derive another design rule:

$$\phi \leq \beta - \alpha - \tan^{-1} \left( \frac{h}{h \cot(\sigma) + p} \right)$$  \hspace{1cm} (2)

If the tilting angle satisfies this rule, we can make sure that the probe can reach the foot of the sample without touching the adjacent pattern.

![Fig. 4 Geometric diagram of scanning situation](image)

B. Results Merging Method

After we get scanning results from each probe with different tilting angle, we have to merge these two measured images through selecting the correct parts of each scanning result to produce the final result. Here, we proposed a results merging method, which is capable of selecting right data based on the slope between each two scanned data point. First, we can express all the scanned data by following expression:

$$z_{in} = P_i(x_n, y_n) = P_i(t_n)$$  \hspace{1cm} (3)

where $i$ means these data come from probe $i$ , and $z_{in}$ is the height value of the scanned point, $P_i(x_n, y_n)$ is the sample profile function, $x_n, y_n$ are the horizontal coordinate of the scanned point. For the reason that we’re scanning with constant sampling frequency with fixed trajectory, we can simply express $z_n$, as function of sampling period $t_n$ , and we can spread all the scanned point on a line, as shown in Fig. 5(a). By calculating the change rate between each two scanned points with the following equation:

$$S_l(t_n) = \frac{P_l(t_n) - P_l(t_n-1)}{t_n}$$  \hspace{1cm} (4)

We can get the slope profile of the sample, as shown in Fig 5(b). Next, because two probes scanned sample with different tilting angle from different directions, we can choose the corresponding parts of scanned results based on the slope. For example, if we approach the sample from left-hand side by probe $I$ and from right-hand side by probe $II$, both with proper tilting angle, as shown in Fig. 5, and because of the probe-sample angle, the probe $I$ will perform better on region with positive slope, and probe $II$ will get more precise data on region with negative slope. Based on the slope profiles and different probe scanning direction, we can derive the following criteria to merge all the data together:

$$P_m(t_n) = \begin{cases} 
   \frac{P_I(t_n) + P_II(t_n)}{2} & \text{for } S(t_n) = 0 \\
   P_I(t_n) & \text{for } S(t_n) > 0 \\
   P_II(t_n) & \text{for } S(t_n) < 0 
\end{cases}$$  \hspace{1cm} (5)
IV. EXPERIMENTAL RESULTS

In the experiment, MATLAB xPC targets were used to achieve real-time control, and MC1602/16 are applied for scanner embedded sensor’s signal feedback. An adaptive complementary sliding mode controller is used in this experiment to control the motion of the scanner, which is capable of dealing with the unmodeled parameters and external disturbances, and this controller is developed in our research group’s previous work [12]. For sending the output control signals, we applied NI 6733 D/A card. The complete setup of the novel dual probes AFM system proposed in this work is shown in Fig. 6.

![Fig. 5 (a)(c) Scanned data arrange by sampling period (b)(d) Slope profile](image)

Fig. 5 (a)(c) Scanned data arrange by sampling period (b)(d) Slope profile

To completely show the performance difference between traditional AFM and the AFM system proposed in this work, we will compare the scanning result of each system by scanning a standard grating. In this experiment, we scanned TGZ-11 standard-grating produced by NT-MDT Inc. It’s a 1-D arrays of rectangular SiO2 steps on Si wafer, and its SEM figure with scale and geometry is as shown in Fig. 7. The pitch of the standard grating is 10 μm and the height is 1.5 μm, and the peak-valley ration is about 7:3. The probes used in this experiment are the Akiyama-Probes, which have cantilever with 310 μm, thickness with 3.7 μm and width with 30 μm. The tip radius is about 15 nm, and tip height is 28 μm. The resonance frequency of the probes used in this experiment are 44.62 kHz and 42.73 kHz respectively. The SEM picture of the probe with geometric features is given in Fig. 8.

![Fig. 6 Experimental setup of the dual-probes AFM system](image)

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![Fig. 7 The standard grating with 10 μm horizontal pitch and 1.5 μm vertical depth (a) sketch map and (b) SEM image](image)

Fig. 7 The standard grating with 10 μm horizontal pitch and 1.5 μm vertical depth (a) sketch map and (b) SEM image

![Fig. 8 SEM image of Akiyama-Probe](image)

Fig. 8 SEM image of Akiyama-Probe

A. Traditional System

First, we scanned the standard grating with traditional AFM setup, which means single probe with monotonic tip-sample angle. The 2D scanning result of a single pitch is given in Fig. 9 and the 3D scanning result is also shown in Fig. 10. The imaging distortions can be observed at the corner part. The side-wall angle of the scanning image is measured to be 74.4°, which failed to reconstruct the vertical feature due to the limitation of tip geometry and tilting angle.
B. Proposed System

For second part of the experiment, the same standard grating was scanned by the proposed dual probes AFM system with scanning results merging algorithm. The tilting angle of the probes are set to be 12°, which comes from the proposed tilting angles deciding mechanism. The scanned images are shown in the following figures. Fig. 11 and Fig. 12 show the scanning results from scanning unit I and scanning unit II. From these two figures, we can easily notice that the corner distortion could be eliminated at one side, respectively. With the proposed merging algorithm, we can merge these two results together, as shown in Fig. 13 where the blue line are the data from scanning unit I and red line are the data from scanning unit II, and the green circles are the data chosen by the merging algorithm. The 3D merging result is also given in Fig. 14. The side-wall angle of the final image is measured to be 86.7°, which is much similar to real profile of the sample compared to traditional system.

Fig. 9 Scanning result of traditional AFM system in 2D

Fig. 10 Scanning result of traditional AFM system in 3D

Fig. 11 Scanning result of probe I

Fig. 12 Scanning result of probe II

Fig. 13 Merging result in 2D

Fig. 14 Merging result in 3D

V. CONCLUSION

In this paper, we designed and developed a novel dual probe AFM system, which can achieve higher scan accuracy and performance compared with the traditional AFM system. A tilting angle deciding method is proposed in this work, which can calculate the necessary tilting angle under different scanning scenarios. By adopting different tilting angle to each probe, we can eliminate scan errors which occur at corner part of the sample. In addition, a result merging method is also proposed in this paper, which provides an objective way to stitch result from different probes together. Experimental results are provided to show the effectiveness of the proposed system and methods. To sum up, a high accuracy AFM system has been proposed in this work.
REFERENCES