A reconstruction method of AFM tip by using 2 μm lattice sample

ZHANG Xiaodong, ZHAO Lin, HAN Zhiguo, XU Xiaoqing, LI Suoyin, and WU Aihua*
Hebei Semiconductor Research Institute, Shijiazhuang 050051, China

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As an ultra-precise instrument to characterize nano-morphology and structure, the morphology of atomic force microscopy (AFM) tip directly affects the quality of the scanned images, which in turn affects the measurement accuracy. In order to accurately characterize three-dimensional information of AFM tip, a reconstruction method of AFM tip using 2 μm lattice sample is researched. Under normal circumstances, an array of micro-nano structures is used to reconstruct the morphology of AFM tip. Therefore, the 2 μm lattice sample was developed based on semiconductor technology as a characterization tool for tip reconstruction. The experimental results show that the 2 μm lattice sample has good uniformity and consistency, and can be applied to the tip reconstruction method. In addition, the reconstruction method can accurately obtain the morphology of AFM tip, effectively eliminate the influence of the "probe effect" on the measurement results, and improve measurement accuracy.

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The principle of atomic force microscopy (AFM) is to obtain the topography by detecting the bending change of the probe cantilever caused by the interaction force between the probe and the sample surface. During the measurement process, the scanning result of the probe on the sample is actually the convolution of the probe tip profile and the surface of the tested sample. Because the probe tip of the AFM cannot be infinitely sharp, the sample morphology obtained contains the three-dimensional information of the probe, that is, there is a "probe effect", which is the main reason for the AFM measurement deviation[1]. In particular, the effect is severe when the probe tip size is close to the line-width feature size, generally manifested as the expansion and broadening of line-width feature. To reduce or correct the probe influence on the measurement results, it is necessary to obtain the probe's three-dimensional information[2].

Under normal circumstances, probe reconstruction methods mainly include the following kinds. The method based on the specification parameters mainly reconstructs the three-dimensional topography of the probe tip based on the parameters of the probe tip geometry, radius and angle provided by the manufacturer. The tip morphology reconstructed by this method is based on the three-dimensional structure under ideal conditions, but the tip is always worn during use[3]. The microscopic observation method uses scanning electron microscopy (SEM), transmission electron microscopy (TEM), and other optical microscopy methods. Microscopic observation method has high resolution and high accuracy, but it requires harsh conditions during the testing process and belongs to destructive testing methods[4]. The probe tip blind reconstruction method is to scan the surface of a characterizer to obtain the information of the tip topography. It has the advantages of zero destructiveness and high accuracy, and has become the preferred choice for probe reconstruction[5].

The method of the probe tip blind reconstruction mainly relies on a calibrated characterizer, and usually uses an array-type micro-nano structure. Therefore, in order to realize the reconstruction of the AFM tip morphology, a 2 μm lattice sample was developed. In addition, an AFM tip reconstruction method based on the 2 μm lattice sample is studied. The reconstruction method can accurately obtain the topography of the AFM tip, effectively reduce the noise of the scanned image, and improve the measurement accuracy.

The development process of the 2 μm lattice sample includes material preparation, oxidation, glue coating, exposure, development, etching, degumming and other process steps, as shown in Fig.1[6]. The oxidation process is to oxidize a layer of SiO_2 film on the Si wafer. The glue coating process is a relatively complex unit in the glue-spraying and developing machine. After the wafer is fixed on the turntable, the organic solvent nozzle is moved to the top of the wafer center under the driving of the robotic arm, and a certain volume of organic solvent is sprayed. When the turntable rotates slowly, the solvent is completely covered on the surface of the wafer under

*E-mail: aihua.wu@139.com

the action of centrifugal force. Before the organic solvent evaporates, the photoresist is evenly coated on the wafer. The exposure process is to irradiate the mask plate, and project the pattern on the mask onto the photoresist through the lens, and then stimulate the photochemical reaction. The etching process is the key process to generate the lattice structure, and the top and bottom surfaces of the grid are required to have small roughness to ensure the measurement accuracy[7]. After the etching process is completed, the photoresist on the wafer surface needs to be removed. The degumming process requires that the photoresist on the substrate should be removed cleanly and thoroughly, and the surface of the substrate should be avoided as much as possible, especially the area without photoresist, and the damage to the device should be avoided as much as possible. Sputtering is to sputter a layer of metallic chromium (Cr) on the upper and lower surfaces of the grid template. The 2 μm lattice sample prepared by semiconductor process is shown in Fig.2.

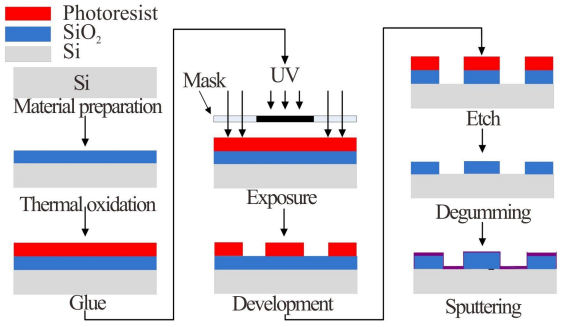

Fig.1 Preparation process of the lattice sample

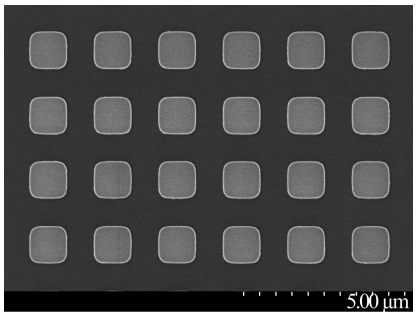

Fig.2 The 2 μm lattice sample under SEM

In order to evaluate the quality of the 2 μm lattice sample, the critical dimension scanning electron microscope (CD-SEM) was used to test the repeatability and stability of the sample. The basic principle of CD-SEM is that when the secondary electron signal detects the sample model, the signal intensity changes significantly. If the image signal-to-noise ratio (*SNR*) is relatively poor, the signal waveform will cause obvious vibration, which will cause measurement errors. CD-SEM is based on the linear approximation algorithm, superimposing the noise wave line of the secondary electron signal and smoothing the signal waveform to reduce the *SNR* of the image. Firstly, for the secondary electron signal waveform, the tangent of the maximum inclination angle is selected as the ramp line. Secondly, the slope of the ramp line is calculated through the derivative relationship. Then, based on the peak waveform of the secondary electron signal, the baseline and the baseline starting point are determined. Finally, the check points are detected through the slope line and the baseline, and the position data, magnification and correction parameters of the sample points to be measured are calculated, and then the geometric dimensional test of the sample is completed[9].

During the test, the single-period grid features of the sample were selected, the test was repeated 10 times to obtain the average value as the fixed value of the grid features, and the repeatability results were calculated by the Bessel formula. The assessment cycle is 1 year, the stability assessment is performed every 2 months, and the stability is calculated by the Bessel formula. It can be seen from Tab.1 that the repeatability and stability parameters of the 2 μm lattice sample are better, and they are maintained within 1.0 nm.

Tab.1 Test data of the 2 μm lattice sample

Frequency	Measurement result (μm)	Repeatability (nm)	stability (nm)
1	1.999 1	0.5	1.0
2	1.999 3	0.4	
3	2.000 8	0.5	
4	1.999 5	0.6	
5	2.001 6	0.3	
6	2.000 4	0.3	

The tip reconstruction method calculates the local topography of the AFM probe tip based on each pixel of the AFM scanned image and the neighborhood topography information, and calculates the topography of the probe with the collection of these local topography information[10]. The relationship between the topography image of the sample scanned by the AFM, the topography of the sample and the topography of the probe tip can be calculated by the mathematical morphology expansion operator as follows

$$I = S \oplus T, \tag{1}$$

where I represents the AFM scanned image, S represents the shape of the sample, $\oplus$ represents the expansion operator, and T represents the shape of the probe tip. In addition, any point of the AFM scanned sample topography image satisfies

$$\forall x \in I, \exists d \in T \mid T \subseteq I + d - x, \tag{2}$$

where d represents the position change of the probe tip topography T in the AFM scanned image I. Then, the tip topography T can be expressed as

$$T_{i+1} \subseteq \bigcap \left[(I - x) \oplus T_i'(x) \right] \bigcap T_i, \tag{3}$$

where T_{i+1} is the (i+1)th iteration of the ith result, $T_i'(x)$ is a set of points of T_i, and these points can be coincident

with the contact points of the AFM scanned image I and the tip apex T at x points.

As a characterizer for probe reconstruction, the 2 μm lattice sample was placed on the AFM vacuum adsorption table. During the scanning process, the dynamic force measurement mode was selected, the AFM scan range was 18 μm×18 μm, the scan points were 256×256, the single line measurement time was 0.78 s, and the probe scan route is shown in Fig.3[11].

After the scan is completed, image processing is performed on the scanned image collected by AFM based on the probe reconstruction algorithm, and the reconstruction effect of the probe tip is shown in Fig.4.

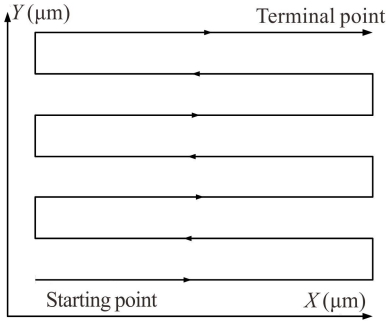

Fig.3 AFM probe scanning route

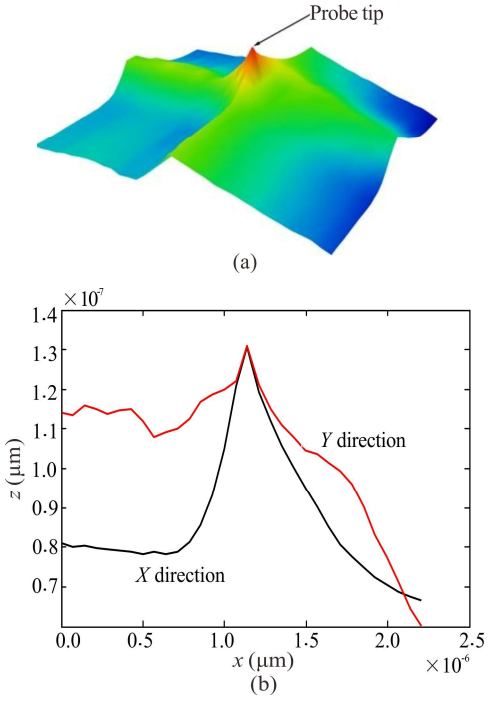

Fig.4 Effect diagrams of AFM tip reconstruction: (a) Three-dimensional effect; (b) Two-dimensional effect

The probe reconstruction algorithm is used to calculate the three-dimensional topography of the probe tip, and then obtain the real sample topography information, which is helpful for AFM to obtain the real measurement information. In order to verify the effectiveness of the AFM tip reconstruction method based on the 2 μm lattice sample, the line-width samples with nominal values of 500 nm, 1 μm and 2 μm were selected as the objects to measure the top line-width value[12]. Through experiments, it is found that the measurement curve after the probe correction has obvious turning points compared with that before probe correction, which means that it is easier to identify the edge position of the line-width feature as shown in Fig.5.

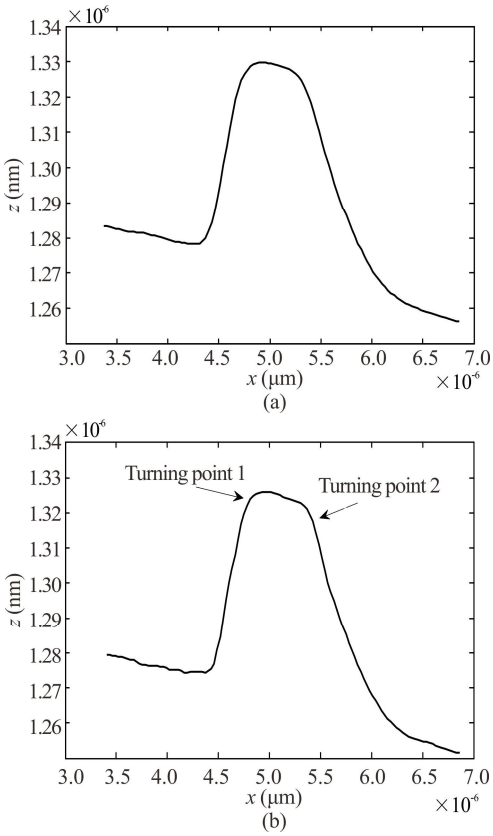

Fig.5 Measurement curves of AFM: (a) Before probe correction; (b) After probe correction

In order to quantitatively analyze the influence of the probe on the measurement results before and after correction, 10 repeated measurements were performed on the line-width samples with nominal values of 500 nm, 1 μm and 2 μm, and the top line-width values measured by CD-SEM were selected as the reference values as shown in Fig.6.

It can be seen from Fig.6 that when the AFM measures the line-width feature, the probe effect will make the AFM measurement results larger. The AFM tip reconstruction method based on the 2 μm lattice sample can effectively reduce the impact of the probe tip on the measurement result and improve AFM measurement accuracy.

With the rapid development of semiconductor technology, the measurement of critical dimensions is the key to improving the performance of components. As a precision instrument for critical dimension measurement, AFM has the advantages of high resolution, low test en-

vironment requirements, and low destructiveness[10]. However, the "probe effect" is the main reason for the deviation of AFM measurement.

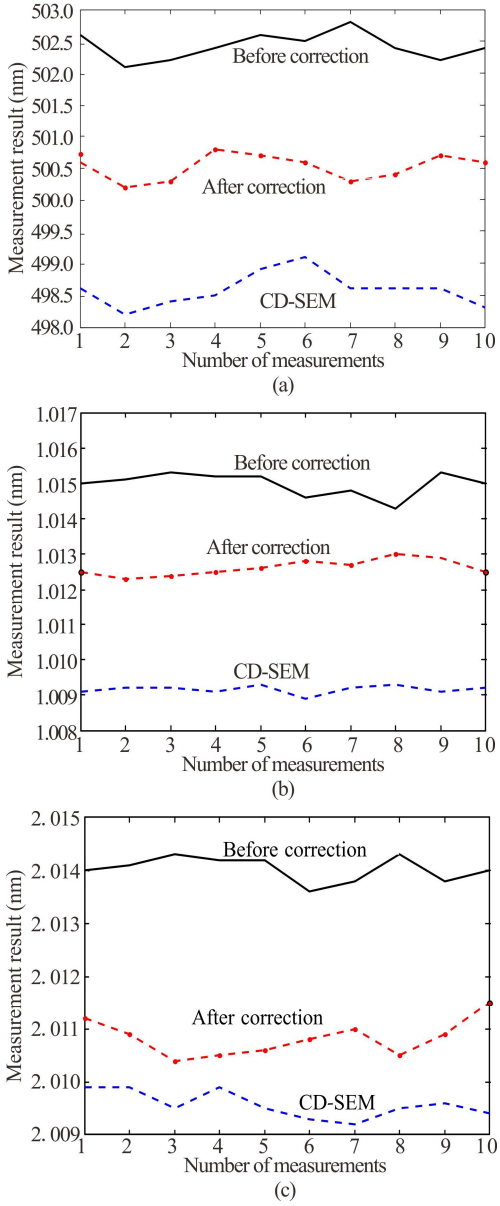

Fig.6 Measurement results before and after correction with different nominal values: (a) 500 nm; (b) 1 μm; (c) 2 μm

In order to effectively reduce the influence of the AFM probe on the measurement results, a 2 μm lattice sample was developed and the AFM tip reconstruction method was studied. Compared with other methods, the use of an array lattice structure is conductive to the collection of data points and improves the accuracy of the three-dimensional reconstruction of the AFM probe tip. Experimental results show that this method can effectively eliminate the influence of the "probe effect" on the measurement results, thereby improving the measurement accuracy of AFM.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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