XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

A LARGE RANGE METROLOGICAL ATOMIC FORCE MICROSCOPE WITH NANOMETER UNCERTAINTY

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Abstract: A metrological atomic force microscope (AFM) with 50mm×50mm×2mm scan range has been designed and constructed. In this paper, the structure and preliminary results are introduced. The precise movement of the sample is driven by a piezoelectric motion stage and air-bearing stage for different scanning range. Four multi-pass homodyne interferometers attached to the metrological frame measure the relative displacement between the probe and sample. A novel AFM head is used to detect the topography at contact mode. Step height standard is measured and the results show that the system is capable of measuring step height with uncertainty of 4 nm.

Keywords: nanometrology, AFM, nanostructure. Interferometer.

1. INTRODUCTION

The atomic force microscopes (AFM) are increasing used in nanoscience research and industry with the ability of surface topography measurement with nanometer resolution since invented in 1986 [1]. Instrument calibration is needed for AFM to trace the measurement to the SI by standards. Metrological AFMs with traceability are developed in national metrological institutes around the world [2-5]. AFMs currently often have a limited scanning range, so large range metrological AFM is desired for semiconductor industrial for characterization of nanostructure and quality control in industry. Recently, several national metrological institutes have begun to develop metrological AFMs with mm scanning range. PTB developed a Metrological large range scanning probe microscope with a measuring range of 25mm×25mm×5mm based on a nano-measuring machine [6]. National Institute of Standards and Technology developed a STM based Molecular Measuring Machine with a measuring range of 50 mm×50 mm×0.1 mm achieving atomic resolution metrology [7]. National Institute of Metrology (NIM) has developed the nano-measuring machine [8].

A large range metrological AFM has been designed and constructed in NIM based on the previous nano-measuring machine with improvement on the reliable and usability. In this paper, the structure of the large range AFM is introduced, including the AFM head and metrological frame.

2. DESIGN OF LARGE RANGE METROLOGICAL AFM

1. Mechanical Structure

As a sub-nanometer resolution metrological instrument, the metrological AFM is designed to minimize the Abbe error and trace to the SI.

The instrument is composed of AFM head, position stage and metrology frame as shown in Fig. 1. The motion of the sample stage is combination of a coarse motion and fine motion. For the large range scanning, the sample stage is moved by air bearing 2-dimensional stage within an area of 50 mm × 50mm. The fine motion of sample is implemented by a nano stage. The AFM head is also driven by piezostage and the scanning in 3 directions are independent to reduce the cross coupling.

Multi-pass homodyne interferometers attached to the metrological frame construct a Cartesian coordinate system, tracing the displacement to the meter definition.

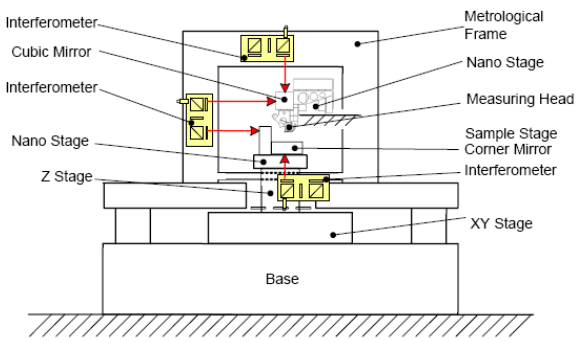

Fig.1 The Schematic of the metrological AFM.

2. AFM measuring head

It is found that the commercial AFM using piezo tube cause coupling of the driver in xy plane and z direction [9]. To scan in x-y plane, the bent of the tube will change the length of tube in z direction. The scanning surface is curved and demands calibration by standards.

An AFM measuring head is designed for the large range metrological AFM. The AFM probe is driven by piezostage. The scanning movements of the probe in 3 directions are independent to reduce the cross coupling. A cube with mirrors on three sides is fixed on the AFM probe as the reference mirrors of interferometer so that the relative displacement between the probe and sample is measured. The probe base is designed to use both optical lever method and tuning fork.

The structure of the measurement head with optical lever method is introduced here as shown in Figure 1. The laser from laser diode is delivered by optical fiber with collimating lens. The collimated laser is focused on the cantilever by a lens. The laser focus spot is 12 um in diameter, less than the cantilever width, to guarantee that the laser is reflected by cantilever. Probe and lens are both mounted on a stage as a whole. The measuring head uses optical lever to amplify the cantilever deflection. The laser beam is reflected by mirrors, and forms an 8 mm diameter spot on the position sensitive detector (PSD).

The deflection of the cantilever $\Delta\theta$ induced by the cantilever displacement Δz is given by [10]

$$\Delta\theta = \frac{3}{2}\frac{\Delta z}{l}, \qquad (1)$$

where l is the cantilever length. The beam deflection is $2\Delta\theta$. The displacement of the cantilever is amplified to the displacement of the spot on the PSD. The spot displacement is given by

$$\Delta s = \frac{3\Delta z d}{l} M \qquad (2)$$

where M is magnification factor of the lens in the detection path, and d is the distance between the PSD and cantilever.

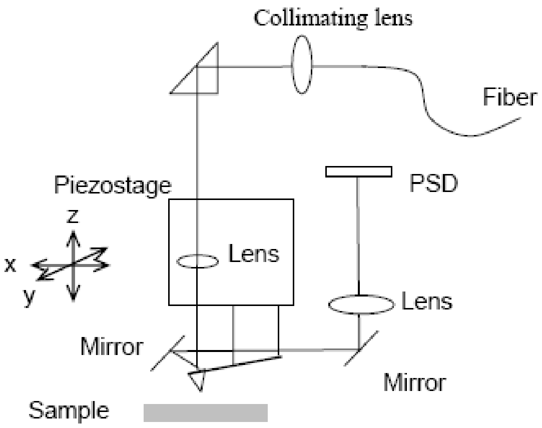

Fig. 1. Scheme diagram of the AFM measuring head.

3. Metrological frame

The metrological frame is constructed to measure the displacement of the sample and probe in three directions by interferometers. The metrological frame is made from Zerodur and the mechanical parts of interferometer are made from Invar to reduce the thermal fluctuation.

To improve the resolution, the displacement is measured with homemade eight-pass interferometers. The Z_{down} interferometer is shown in Fig. 2 for instance. The He-Ne laser from polarization maintaining fiber is colimated and split into two linear polarized beams by PBS and directed to the measurement and reference mirrors respectively. The laser beams repeat 4 times. The output beam is detected by quadrate detection [11]. A period of one circle corresponds to λ/8, corresponding to 79 nm. The phase in one circle is interpolated by a look up table with 4096 subdivision. So the resolution of interferometer is 0.02nm.

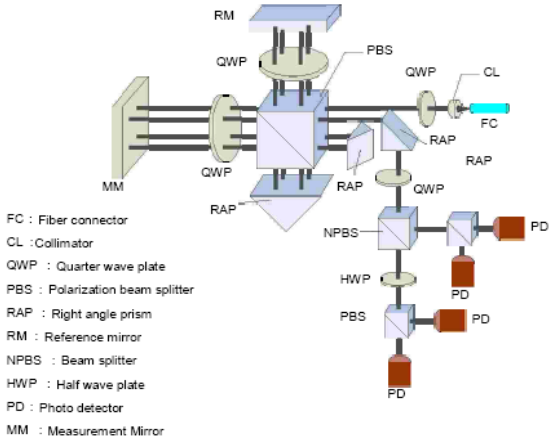

Fig. 2. The schematic of the multi-pass interferometer.

The arrangement of the interferometers is shown in Fig. 3. The absolute displacements of the probe and sample in z direction are measured respectively from top and down. The relative displacements of probe and sample in x and y directions are measured in differential mode by x and y interferometers. The interferometers are mounted on the frame and supported with screws. All the measuring beams of the four interferometers are adjusted to construct a Cartesian coordinate system.

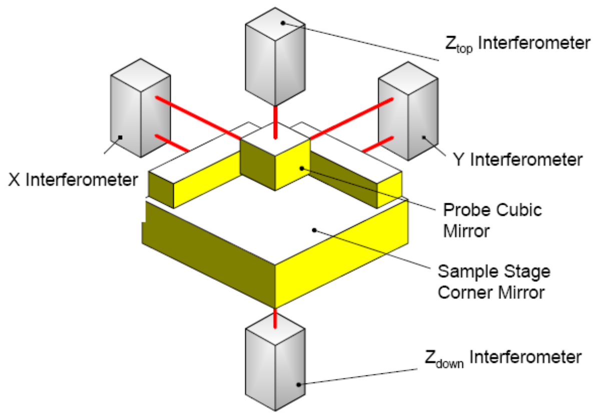

Fig.3. The arrangement of interferometers of the metrological frame.

The probe tip is positioned in the intersection of the interferometers to minimize the Abbe error. The AFM probe is driven by a piezostage in three orthogonal directions. A cube with mirrors on three sides is fixed to the probe and scans with the probe as a whole. The sample stage is mounted on a corner mirror with high reflectivity on three sides. The corner mirror is driven by nano-positioning stage. The stage is mounted on a large range positioning stage with air bearing for large range scan.

3. EXPERIMENT RESULTS

To test the resolution of the AFM head at contact mode, the probe is lift approaching the sample by piezoelectric actuator. The step wave driving signal is applied to the piezostage and the displacement of the stage is detected by capacity sensor. The step motion of the deflected laser beam is also detected. The result is shown in Fig. 4. The motion step of the probe in z direction is 0.5 nm. The displacement of the spot shows the consistent step as the displacement of the probe. The distinct step of the PSD output demonstrated that the resolution of the measuring head is better than 0.5 nm. The result shows a peak-to-peak noise of 0.2 nm.

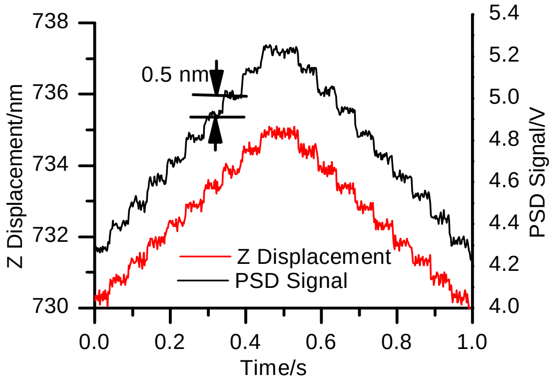

Fig. 4. PSD signal as the step motion of the probe in z direction.

The metrological AFM has been tested with different scan range. Fig.5 shows AFM measurement of a step height standard sample. The scan region is 100 μm×8 μm. The step height measured by interferometers is 780.4 nm±3.6 nm. The tilt is caused by the sample mount. The measured profile of a grating sample with 10 μm pitch is shown in Fig.6 to demonstrate the large range scan. The sample is scanned by the air-bearing stage directly with a length of 1 mm.

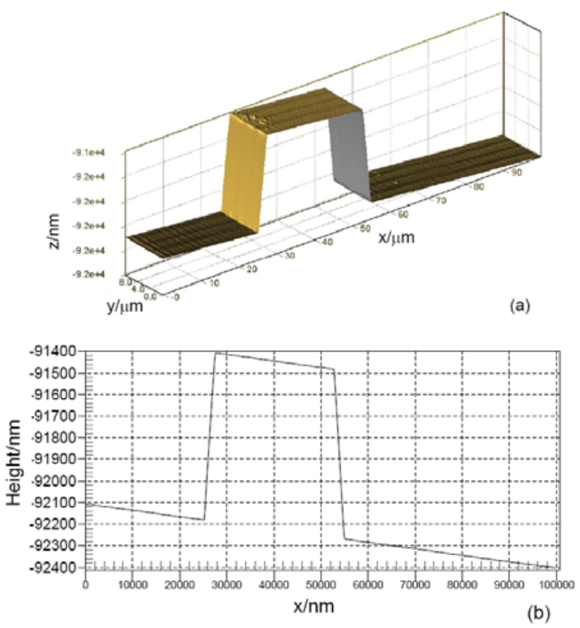

Fig.5. AFM measurement of a step height sample: (a) 3D profile and (b) one cross section line.

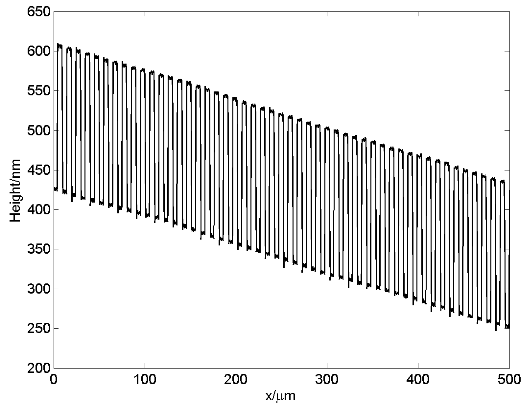

Fig.6. AFM measurement of a grating sample.

4. CONCLUSION AND DISCUSSION

A large range metrological AFM is designed to establish a traceable standard with nanometer uncertainty. The AFM probe is driven by piezostage and the scanning movements of the probe in 3 directions are independent to reduce the cross coupling. Large range scan and small scan range are performed by coarse and fine positioning stages respectively. Muti-pass interferometer is designed to measure the relative displacement between the sample and probe. By scanning the step height sample, the AFM demonstrates a 4 nm uncertainty in z direction.

5. REFERENCES

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