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METROLOGICAL ATOMIC FORCE MICROSCOPE AND TRACEABLE MEASUREMENT OF NANO DIMENSION

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Abstract: A metrological AFM is designed to establish a traceable standard with nanometer uncertainty. The principle and design of the instrument is introduced in this paper. The displacement of the sample is traced to the SI unit by interferometers. The metrological AFM is applied to step height and line width measurement. The results are compared with optical instrument and profilometers. The metrological AFM participates step height international comparison and the result shows an uncertainty less than 2 nm.

Keywords: AFM, nanometrology, step height.

1. INTRODUCTION

With the development of semiconductor industrial, many techniques such as integrated circuit, MEMS, require measurement with nanometer accuracy. The main industrial countries around the world have been working at establishing metrological specifications and instruments relevant to nanotechnology. The Discussion Group 7 (DG7) for nanometrology under the Consultative Committee for Length's Working Group on Dimensional Metrology (CCL-WGDM) decided at its June 1998 meeting at the BIPM to perform a comparison for five different types of artefacts in order to set up an international nanometrological regime.

Atomic force microscopes (AFMs) provide high resolution and are used to measure the nano and micro size structures and surface topography and roughness [1]. Due to the high scanning rate, AFM is applied in industry for wafer detection. The probe or the sample is usually scanned by piezotube and the displacement is measured by capacitive sensors. Due to the nonlinearity and hysteretic of the piezo scanner, AFMs with metrological abilities are required to ensure the measurement quality.

In Natinal Institute of Metrology (NIM), metrological AFMs are developed and improved. In this paper, we report the instrument and calibration application in step height and line width measurements.

2. METROLOGICAL AFM

2.1 Principle of AFM

AFM is based on the interaction between a sharp tip and samples. The principle of AFM is demonstrated in Figure 1.

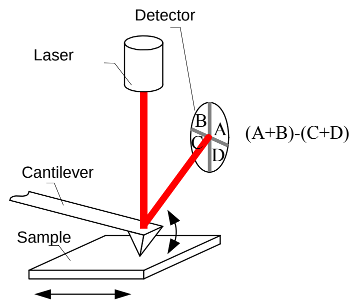

Figure 1. AFM with beam deflection technique

When the cantilever is approaching the surface, the interaction between the tip and sample will cause bending of the cantilever. Light from laser is reflected by the cantilever onto a quadrant detector. So the position of the laser spot on the detector moves and the signal is detected for feedback control of the piezostage, to keep the distance between the tip and sample constant.

For the commercial AFM using piezo tube to drive the probe, it is found that the bent of the tube will change the length of tube in z direction when scanning in xy plane, [2]. The scanning surface is curved and demands calibration by standards. The displacements also require calibration for the nonlinearity of the piezoelectric actuators.

2.2 Metrological AFM

Most of the metrological AFMs are equipped with interferometers to calibrate the position [3] and trace the displacement to SI unit.

By the incorporation of three miniature laser interferometers, a commercial AFM has been modified to metrological AFM with the cooperation with Ilmenau Technical University and Physikalisch-Technische Bundesanstalt [4].

The design is shown in Figure 2. The sample stage is moved by 3D scanner. The flexure hinge stage is driven by three piezoceramics in three directions with scanning range of 70 μm×15 μm×15 μm. The displacements in three axes are traceable by interferometers with 633 nm laser. To eliminate the Abbe error, the tip of the AFM is placed at the interception of the interferometer beams.

The AFM head use confocal detection method to detect the cantilever deflection instead of quadrant detector.

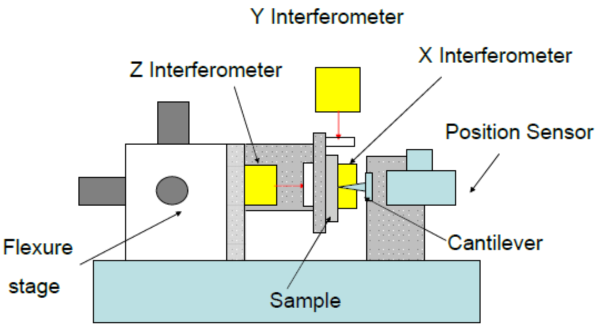

Figure 2. Structure of metrological AFM

The displacement is sent by computer to the D/A converter, to drive the piezostage. The difference between the expected position P and the real position measured by interferometers is P_s is

$$\mathbf{\Delta P} = \mathbf{P} - \mathbf{P_s} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} - \begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix}. \quad (1)$$

The difference is caused by the motion coupling between different axes. The relation of the measured position by interferometers P_s is a function of the ideal position $\mathbf{P} = [x \quad y \quad z]^T$.

$$\mathbf{P_S} = f(x,y,z) = \begin{pmatrix} xtx \\ xty \\ xtz \end{pmatrix} + \begin{pmatrix} ytx \\ yty \\ ytz \end{pmatrix} + \begin{pmatrix} ztx \\ zty \\ ztz \end{pmatrix}, \quad (2)$$

where *tx*, *ty* and *tz* are the coupling error to x, y ,and z axis respectively. The set position can be derived by the inverse function

$$\mathbf{P} = f^{-1}(x_s, y_s, z_s) \quad (3).$$

Correction equations are used to compensate the stage displacements error.

3 MEASUREMENT RESULTS

The nano-structure dimensions Step height, line width and pitch are three important parameters of nano-structure dimensions in integrated circuit manufacturing. To provide consistent and traceable measurement, the transfer standards are used to calibrate the instrument. The standards are calibrated by metrological instrument.

Step height standards are utilized to calibration the z axis of microscopes and topography measuring instrument. The step sample is shown in Figure 3. It is fabricated by Si substrate with SiO2 step square and bars. Ten step heights are fabricated with nominal height 25nm; 50nm; 100nm; 200nm; 300nm; 400nm; 600nm; 900nm; 1000nm; 1800nm. The samples are measured with profilometer and AFM to compare different instrument and methods. The results are shown in Table 1.

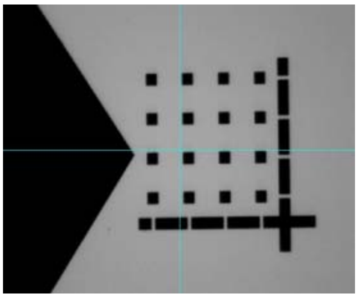
Figure 3. sample of step height

Table 1. Step height standards results measured with different instruments（nm）

No	Profilometer	Metrological AFM	Profilometer (PTB)	AFM (PTB)
1	301.0	300.5	299.1	301.3
2	396.0	393.5	392.4	391.7
3	593.5	598.9	598.8	595.6
4	924.0	922.7	926.3	923.6
5	1079.0	1077.0	1081.1	1075.1
6	1739.0	1730.0	1750.9	1722.7

The result measured with different instrument demonstrated consistent result with about 10 nm deviation.

To establish nanometrological regime, international comparison of nano-standards stated from 2000. Step height international comparison with PTB as the pilot laboratory has accomplished [5]. The standards are Si substrates with SiO_2 steps coated with Cr as shown in Figure 4. The measured region is 100×100 μm^2.

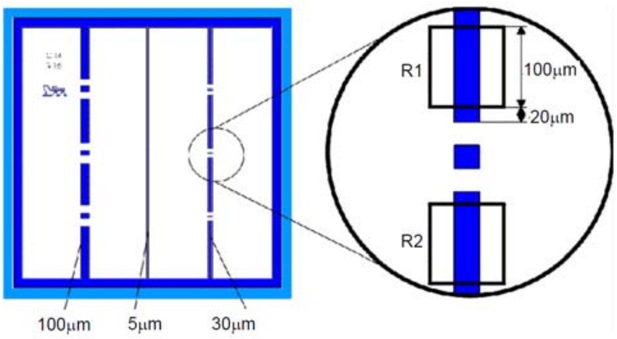

Figure 4. Standard sample and measurement region

The scanning range of the AFM is 70×12μm with 400×200 pixels. The 100 um region is scanned three times from top down.

According to the international roughness standard, the step height is measured as the Figure 5 shows. 15μm on the step center profile is scanned and two 15μm profile on the baseline. The line is least square fitting to obtain the step height. The line step heights at different positions are averaged.

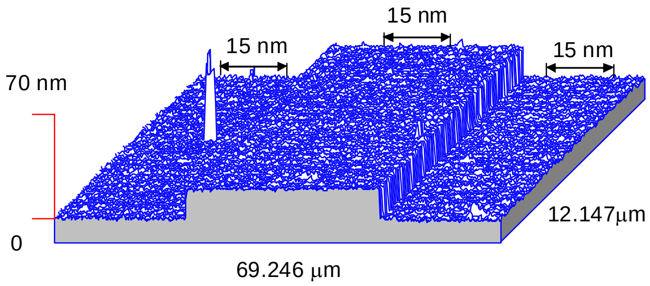

Figure 5 . Image of a 20 nm step sample measured by metrological AFM.

15 national metrology institutes joined the comparison with different instrument. The result of the 300 nm step height is shown in Figure 6. The uncertainty of measured result of NIM is no more than 2 nm.

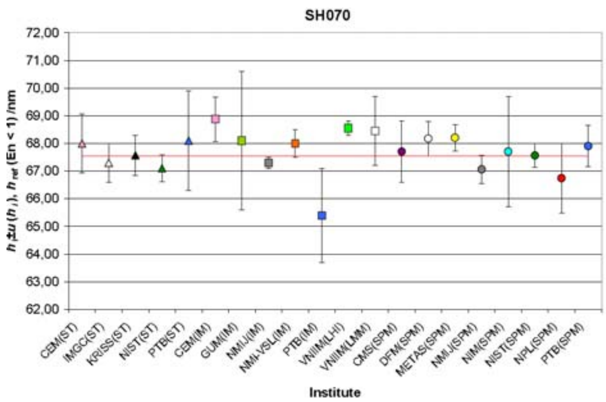

Figure 6. Measured step heights h_i of the institute and reference value h_{ref} (red line) of 70nm step height sample [5].

Line width is also a significant parameter which is decreasing with the development of semiconductor industry. For the probe tip of AFM has finite size, the line width is influenced by the tip size of the probe. The diameter of the probe tip is about 10 nm. The measured profile of step edge is a convolution of the tip shape and the real step profile, as demonstrated in Figure 7.

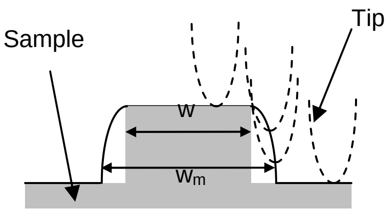

Figure 7 Influence of the SPM tip to the line width w_m from the measured profile.

The distance of the left and right edge of the measured profile is related to the height. To interpret this effect, the widths of samples are measured with metrological AFM at different height from the baseline. The results are shown in Table 2 and the results traced to the optical line width standards of NIST are also shown. The width measured at 30%-50% height is comparable to the reference value, less than 50 nm. The width measurement is critical and the edge effect is dependent on the instrument based on different principle.

Table 2 line width measured at different height

No	Optical line width/ µm	Metrological AFM line width/µm				
		20%	30%	40%	50%	60%
1	0.83	0.82	0.84	0.86	0.87	0.88
2	1.78	1.73	1.76	1.79	1.80	1.82
3	2.75	2.71	2.74	2.75	2.77	2.79
4	3.76	3.69	3.72	3.74	3.75	3.77
5	4.75	4.70	4.73	4.75	4.76	4.78
6	5.74	5.71	5.73	5.75	5.77	5.78
7	6.77	6.70	6.73	6.75	6.77	6.79
8	7.77	7.75	7.77	7.79	7.80	7.81
9	8.73	8.74	8.77	8.78	8.79	8.80
10	9.77	9.76	9.78	9.80	9.82	9.83

However this edge effect is not significant for step height or line pitch measurements of the period structure, for the edges have same influence and can be eliminated.

4. CONCLUSION

A metrological AFM is designed to establish a traceable standard with nanometer uncertainty. The sample stage is driven by piezostage and reflectors are mounted on the stage as reference mirrors of interferometers, so that the movements of the probe in 3 directions are traceable. The tracing system is to calibrate the standards with metrological AFM, and then calibrate AFM with the standards.

For step height measurement, metrological AFM has comparable result with other instrument and the AFM demonstrated uncertainty U_{95}<2 nm. However, the shape of the AFM probe tip and the fabrication process influent the measured sample profile, and the width is related to the measurement position. So the definition of the line width is under study to retrieve the real width. It is found that the 40% height position of AFM profile is a reliable width compared to that of optical microscopy.

The scanning range limits the application of the metrological AFM. A Large range metrological AFM has been developed in NIM to calibrate larger samples [6].

5. REFERENCES

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