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Pitch Measurement of 150 nm 1D-grating Standards Using an Nano-metrological Atomic Force Microscope

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ABSTRACT

Pitch measurements of 150 nm one-dimensional grating standards were carried out using a contact mode atomic force microscopy with a high resolution three-axis laser interferometer. This measurement technique was named as the 'nano-metrological AFM'. In the nano-metrological AFM, three laser interferometers were aligned precisely to the end of an AFM tip. Laser sources of the three-axis laser interferometer in the nano-metrological AFM were calibrated with an I_2-stabilized He-Ne laser at a wavelength of 633 nm. Therefore, the Abbe error was minimized and the result of the pitch measurement using the nano-metrological AFM could be used to directly measure the length standard. The uncertainty in the pitch measurement was estimated in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM). The primary source of uncertainty in the pitch-measurements was derived from the repeatability of the pitch-measurements, and its value was about 0.186 nm. The average pitch value was 146.65 nm and the combined standard uncertainty was less than 0.262 nm. It is suggested that the metrological AFM is a useful tool for the nano-metrological standard calibration.

Key Words : AFM, Calibration, Laser interferometer, Precision measurement, Uncertainty

1. Introduction

According to the 'Metrology' part of 'The International Technology Roadmap for Semiconductor', the required measurement resolution of the linewidth is about 100 ~ 150 nm[1]. Especially, in the semiconductor area it is necessary to measure the critical dimensions on the nano-meter scale.

It is difficult to measure and certificate the pitch and step value of the nano-metrical scale dimensions by using a high-precision measurement machine in a factory or in-line. Also, the precise control of the environment is very difficult. Therefore, the comparison of the feature dimensions with the calibrated standards is a good solution to measure the nano-meter scale dimensions.

Metrological AFMs for certifying the standards were developed by several national metrology institutes. First, a calibrated AFM (C-AFM) was developed at the National Institute of Standards and Technology, United States of America in 1994[2]. A flexure stage driven by piezoelectric transducers was used for scanning. The position sensors used for the C-AFM were a laser interferometer for XY-axis plane and a capacitance sensor for the Z-axis. The laser interferometer and capacitance sensor were calibrated using an I_2-stabilized He-Ne laser. At the Swiss Federal Office of Metrology

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and Accreditation, a long-range AFM profiler was developed in 1998[3]. The long scanning range of about 380 μm for the X-axis could be achieved by using a leaf spring stage. The X-axis position of the stage is detected and controlled using a laser interferometer. A metrological head is used as the Y- and Z-axis stage of the AFM profiler. At the Physikalich Technishe Bundesanstalt in Germany, a metrological scanning force microscope was also developed in 1998[4]. It has a XYZ-axis laser interferometer and a XYZ-axis capacitance sensor for monitoring and control of the stage position. A 3D flexure hinge made of Invar was used for scanning. The measuring range is 70 μm × 15 μm × 15 μm, and the resolution for each interferometer is about 10 nm, 0.25 nm, and 0.25 nm, respectively. For removing the Abbe errors, the laser interferometer was precisely aligned to the end of the AFM tip. On the other hand, in 1997 the Danish Institute of Fundamental Metrology in Denmark developed analysis methods for accurate characterization of SPM by imaging and automated image processing using a commercial AFM with capacitive position sensors[5]. They improved the previously reported algorithm for calculation of the unit cell by sub-pixel Fourier analysis for high accuracy.

In 1999 the National Metrology Institute of Japan, AIST, developed a 'nano-metrological AFM' system with a ultra-high resolution three-axis laser interferometer[6,7]. The position of the scanning stage was monitored and servo-controlled using interferometer signals in real time. Since laser sources of the interferometer were calibrated with an I_2-stabilized He-Ne laser, the uncertainties in measurement could be substantially minimized due to its direct traceability to the length standard compared with other metrological AFMs.

To establish the metrological equivalence between the national metrology institutes, various comparisons among international organizations have been performed. Recently, supplementary key comparisons in the field of nano-metrology have been carried out. Round-robin measurements of one-dimensional gratings with nominal pitches of 700 and 300 nm were completed, and the results are available from the data base of the Bureau International des Poids et Mesures[8]. In the round-robin measurements, optical diffractometers and scanning probe microscopes (SPMs) were mainly used. In addition, measurement of one-dimensional gratings with a nominal pitch of 240 nm was also carried out in 2003[9].

2. Experimental Setup

2.1 Nano-metrological atomic force microscope with a three-axis laser interferometer

The nano-metrological AFM consists of three units including a stage unit, an AFM probe unit and an interferometer unit as shown Fig.1. The stage unit is composed of a piezo-driven XY-axis leaf spring stage and a Z-axis scanner tube piezo actuator. The scanning area of this stage unit is about 17.5 μm (X) × 17.5 μm (Y) × 2.5 μm (Z). The XYZ stage position is servo-controlled using the interferometer signals in real time.

The AFM probe unit of the nano-metrological AFM is operated on a scanning type stage and is operated in the contact mode under a constant force. The distance between the end of the AFM tip and the sample surface is controlled to be constant to maintain a constant force.

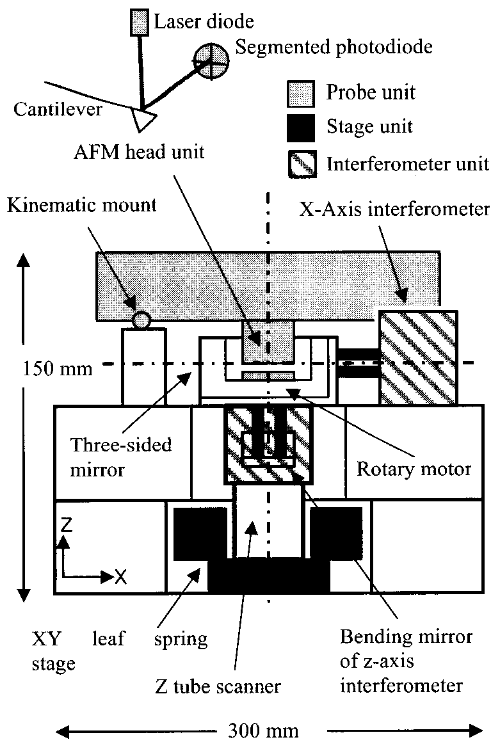


Fig. 1 Cross-sectional drawing of the main unit of the nano-metrological AFM. It consists of a stage unit, an AFM probe unit and an interferometer unit[9].

Fig. 2 shows the block diagram of the nano-metrological AFM. A bending mirror of the Z-axis interferometer is integrated into the Z-axis scanner tube. A three-sided moving mirror for the XYZ interferometer unit is placed on top of the Z-axis scanner. The interferometer has four optical paths in each axis and the total resolution of the interferometer unit is theoretically about 0.04 nm. Laser sources of the interferometer unit are frequency-stabilized He-Ne lasers with a wavelength of 633 nm (model 117A, Spectral Physics Ltd.). The laser frequency is calibrated using an I_2-stabilized He-Ne laser before measuring the one-dimensional grating pitch. Therefore, measurement result of the nano-metrological AFM directly gives the length-standard-traceable calibration pitch values of the nano-metrological standards.

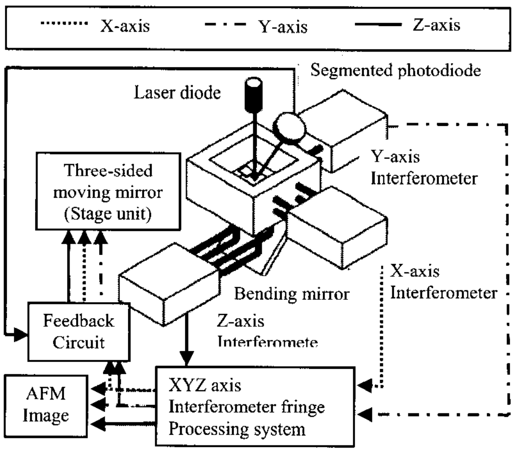


Fig. 2 Block diagram of the nano-metrological AFM system. The stage position is servo-controlled using the interferometer signals in real time[9].

A sample is set on an ultrasonically driven rotary stage which adjusts the lateral rotational angle of the sample. The stage is mounted inside the three-sided mirror. For determining the position of the AFM cantilever, the force applied to a cantilever in the contact mode is detected using a conventional optical lever method.

2.2 One-dimensional grating standard for a pitch of 150 nm

One-dimensional grating standard for a pitch of 150 nm was manufactured by 'Advanced Surface Microscopy Ltd'. It is used for the X, Y-axis(lateral direction) calibration of the SEM and other nano-metrological instruments. In this grating standard, an average pitch value was about 145.5 nm, and the accuracy was within 0.5 nm. This value was determined by 'DiscTrackPlus'[13]. This grating was made of aluminum lines on a glass substrate.

Fig. 3 shows an AFM image of the one-dimensional grating standard. The measurement area of Fig. 3 is 1 μm (X) × 1 μm (Y)[10].

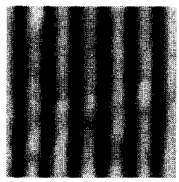


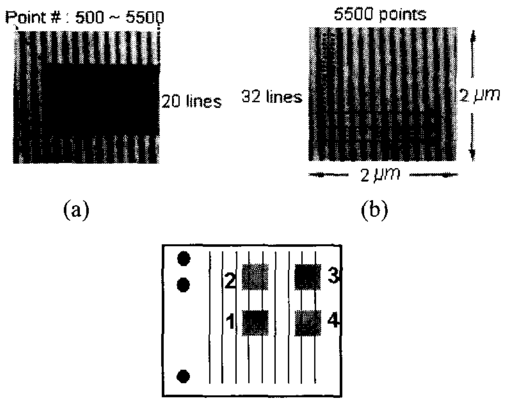
Fig. 3 AFM Image of one-dimensional grating[10].

2.3 Measurement procedure

The measurement conditions are as follows: Four measurement points, as shown by the shaded boxed in Fig. 4(c), were selected. The measurement area at each measurement point was about 2 μm (X) × 2 μm (Y) as shown Fig. 4(b). At measurement point #1 the measurement of pitch value was carried out 3 times. Multiple measurements were for the repeatability of the pitch of the one-dimensional grating standard. At measurement points #2, #3, and #4, the measurements were carried out only once at each measurement point for uniformity of the one-dimensional grating standard. The scanning direction was almost perpendicular (X-axis direction) to the line of the grating patterns (Y-axis direction). One scanned image had 32 profile lines. Twenty lines out of 32 were used for estimating the pitch value. The profiling data of 20 scanning lines were obtained in one measurement, and the measurement point number of one measurement line was 5500 points. 501 ~ 5500 points were also selected for one measurement line as shown Fig. 4(a). It is not used for the initial measurement data (data #1 ~ 500) for the analysis, because the data is unstable. Yawing, rolling and pitching for X-axis direction scanning were estimated before measurement of the pitch values[6]. The sampling frequency of the XYZ interferometer signals was 1.125 kHz, which was decided according to the sampling interval of approximately 0.18 nm. In order to eliminate any damage to the sample surface, the spring constant of the cantilever probe must be small. For the measurements, a triangular micro-cantilever was selected and its nominal spring constant was 0.1 N/m. It was manufactured by 'Microlevers^{TM}'. The cantilever length was 140 μm, width was 18 μm, thickness was 0.6 μm, and the resonant frequency was 120 kHz.

Table 1 Measurement points of one-dimensional grating standards using nano-metrological AFM.

Measurement point	Number of measurement		
1	3	Repeatability	Uniformity
2	1	-	
3	1	-	
4	1	-	



(a) (b) (c)

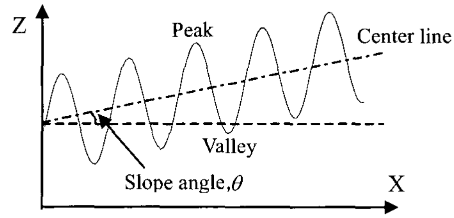
Fig. 4 Position and area of the measurement point in the one-dimensional grating standard. Shaded area of (a) is taken for analysis. (b) is the entire measurement area, and (c) is the position of the measurement point.

The average value of these pitches was defined as the pitch values at all the measurement points and the standard deviation of the pitch values was also defined as the standard deviation at all the measurement points. Measurements were performed in an environment-controlled room at 20 ± 0.5 °C, 100 ± 1 kPa and RH 50 ± 5 %. Temperature, pressure and humidity in the measurement room were monitored during one measurement for about 5 minutes. The temperature in the neighborhood of the sample was measured simultaneously.

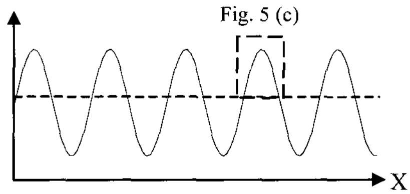
3. Procedure of pitch value calculation and uncertainty evaluation in measurement

3.1 Calculation procedures of pitch value

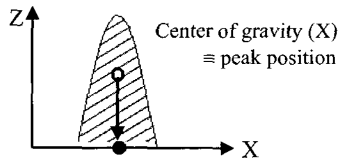
The calculation procedures of the pitch value shown in Fig. 5 were as follows[9].



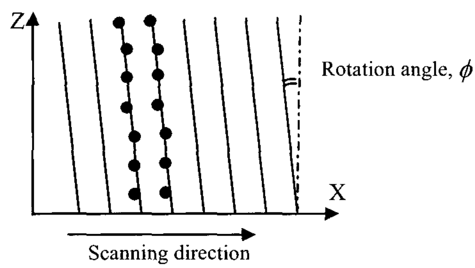
(a) Line profile of pitch measurement



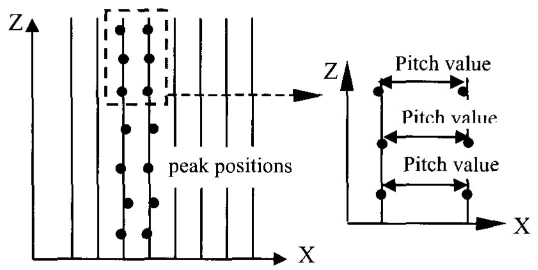
(b) Slope corrected line profile



(c) Determination of peak position



(d) Rotation angle in XY-Plane



(e) Corrected peak positions (f) Pitch values

Fig. 5 Calculation procedure for the pitch values[9].

Fig. 5(a) shows one line of the 20 line profiles obtained by scanning. The centerline of the undulations of the profile is obtained by the least squares linear fitting method using the peak and valley points. The slope of the line profiles was calculated and corrected by this centerline. Fig. 5(b) shows the slope-corrected line profile by removing the slope.

Fig. 5(c) shows an enlarged profile of Fig. 5(b). The area surrounded by the profile curve with the local peak point and the base line (X-axis) is calculated and the X position of the center of gravity of this area is defined as the representative value of the peak position of each pitch.

Fig. 5(d) shows the peak position line in the XY plane. The ribs are not precisely parallel to the Y-axis direction if we try to adjust the angle by using the ultrasonic rotary motor. The correction of the rotational angle in the XY plane is required to make the ribs parallel to the Y-axis direction and to obtain the pitch values. It means that the scanning direction (X-axis) and the ribs of the grating patterns (Y-axis) are not exactly perpendicular. When we plot the XY-coordinates of the peak positions for the 20 scanning lines of the same rib, the result can be approximated as the straight line shown in Fig. 5(d). This eventually leads to a cosine error. The rotation angle is corrected using the slope of the approximated line as shown in Fig. 5(e).

The pitch value is taken to be the distance between two neighbouring peak positions in Fig. 5(f). Pitch values are obtained and the average of these values is taken to be the pitch value at the measurement point.

3.2 Uncertainty Evaluation

The uncertainty in one-dimensional grating pitch measurement using the nano-metrological AFM system is estimated. The sources of uncertainty are divided into five classes as follows:

- Pitch measurement (Z_i)
- Laser interferometer (λ)
- Refractive index of air (C_i)
- Sample Temperature (C_t)
- Slope correction (C_s)

The estimation method of uncertainty in measurement and its expression are based on the Guide to the Expression of Uncertainty in Measurement (GUM)[11]. The sources of uncertainty and standard uncertainty components in the pitch measurements are shown in Table 2.

Table 2 Sources and estimated values of uncertainty in the pitch measurement using the nano-metrological AFM[9].

Source of uncertainty	Value (nm)
(1) Pitch measurement	
- Repeatability	1.86E-01
- Non-uniformity	1.41E-01
(2) Laser interferometer	
- Frequency variation of laser	1.21E-02
- Frequency stability of laser	6.59E-06
- Changes in the dead path (temperature)	1.17E-06
- Change in the dead path (thermal expansion)	1.17E-06
- Interferometer resolution	2.23E-02
- Cosine error in optical alignment	1.02E-05
- Abbe error	1.09E-02
- Change in optical path	2.06E-03
- Interferometer nonlinearity (cyclic error)	1.15E-01
(3) Refractive index of air	
- Refractive index of air (temperature)	9.48E-05
- Refractive index of air (humidity)	3.12E-06
- Refractive index of air (pressure)	3.34E-04
(4) Sample temperature	
- Difference in the sample temperature	6.94E-04
- Thermal expansion	6.95E-04
(5) Slope correction	
- Cosine error (vertical inclination)	6.98E-04
- Cosine error (lateral inclination)	6.86E-04

For pitch measurement, two sources of uncertainty are obtained. One is derived from the repeatability of the pitch measurement. The standard uncertainty derived from the repeatability of the measurements is decided from the dispersion of the three pitch values at point# 1 in Fig. 4(c). The other is derived from the non-uniformity of the sample. The non-uniformity is given by the standard deviation of the four pitch values obtained at points # 1 ~ 4 in Fig. 4(c).

For the laser interferometer, nine sources of uncertainty are estimated as follows. First, the uncertainty derived from the frequency variation of the laser is determined from the maximum Allan variance at various gate times. Uncertainty derived from the frequency stability of the laser is estimated from the maximum change in the measured frequency over two years. Uncertainty derived from the change in the dead path (temperature change component) is determined from the maximum temperature changes in the interferometer base plate. Uncertainty derived from the changes in the dead path (thermal expansion of the interferometer base plate component) is evaluated from the unreliability of the thermal expansion coefficient of the base plate. Uncertainty derived from interferometer resolution is defined as a single up and down pulse of the interferometer signal. Uncertainty derived from the cosine error in the optical alignment is given by the maximum measured value during the alignment of the optical parts. Uncertainty derived from Abbe error and changes in the optical path are estimated by the geometry. Finally, uncertainty derived from the interferometer non-linearity (cyclic error) is given by the following procedure. The stage is driven in the X-axis direction by a triangular wave signal and its displacement is detected by the X-axis interferometer. The least-squares-fit curve of the obtained interferometer signals is calculated and the obtained residual error is used as the interferometer non-linearity.

For refractive index of air, three sources of uncertainty are derived from the change in the refractive index of air. Data for temperature, humidity and air pressure in the experimental room are approximated to have a rectangular distribution obtained using the temperature, humidity and air pressure data gathered during measurements throughout one year. The change in the refractive index of air is calculated using Edlen's equation with the humidity and pressure of air being fixed at the middle value of the distribution and only the temperature of air being changed[12]. The source of uncertainty derived from the change in the refractive index of air (temperature component) is decided using the change in temperature. The other two sources of uncertainty are derived from the change in the refractive index of air estimated in the same manner.

For sample temperature, two sources of uncertainty derived from the sample temperature are estimated. One is derived from the change in sample temperature in one year. The other is given by the thermal expansion of the sample.

For slope correction, two sources of uncertainty derived from the slope correction are estimated. One is derived from the centerline slope of one line profile. The other is derived from the cosine error of lateral inclination and is determined from the rotational angle.

4. Result and Conclusion

Table 3 shows the results for the measured pitch values of one-dimensional grating sample. Non-uniformity and the dispersion of measured pitch values in a sample were approximately same as the repeatability of measured pitch values at one measurement point of a sample.

Table 2 shows the sources of uncertainty and also the estimated results of uncertainty in the measurement of the sample. The combined uncertainty, u_c is the square root of the sum of squares of each standard uncertainty, u_i and it is expressed as

$$u_c = \sqrt{\sum u_i^2} = \sqrt{(1.55\times10^{-1})^2 + (9.89\times10^{-6}\times p)^2} \qquad (1)$$

where, p is the pitch value (in nm).

Precision measurements of 150 nm pitch one-dimensional grating standard were carried out using an AFM system with a high resolution three-axis laser interferometer (nano-metrological AFM). The average value of the pitch, p and the combined standard uncertainty of the sample, u_c in the measurements were 146.65 nm and about 0.262 nm, which was less than 0.18 % of the pitch value, p, respectively. The major sources of uncertainty in the measurement were derived from the non-uniformity and repeatability of the sample as shown Fig. 6. The result satisfies the requirement for precision measurement in nano-metrical scale and calibration for nano-metrological standards.

Table 3 The pitch values at all measurement points on the sample

Measurement point #		Pitch value (nm)	Standard deviation (nm)
1	1	144.80	4.43
	2	144.56	4.53
	3	144.43	4.29
2		144.76	4.63
3		144.60	5.42
4		144.73	4.72
Average (nm)		146.65	4.67

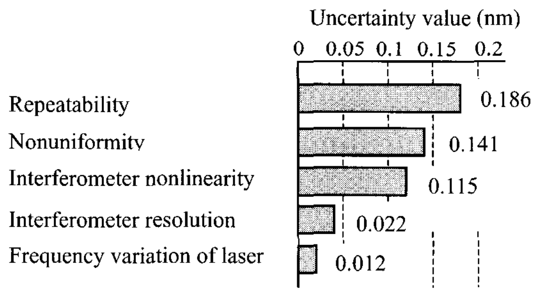


Fig. 6 The large sources of uncertainty.

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References

1. Semiconductor Industry Association, The National Technology Roadmap for Semiconductor, 1999.
2. Schneir, J., McWaid, T. H., Alexander, J. and Wilfley, B. P., "Design of an atomic force microscope with interferometeric position control," J. Vac. Sci. Technol. B, Vol. 12, No. 6, pp. 3561-3566, 1994.
3. Meli, F. and Thalmann, R., "Long-range AFM profiler used for accurate pitch measurements," Meas. Sci. Technol., Vol. 9,No. 7, pp. 1087-1092, 1998.
4. Bienias, M., Gao, S., Hasche, K., Seemann, R. and Thiele, K., "A Metrological scanning force microscope used for coating thickness and other topographical measurements," Appl. Phys. A, Vol. 66, pp. S837-S842, 1998.
5. Jorgensen, J. F., Jensen, C. P. and Garnaes, J., "Lateral metrology using scanning probe microscopes, 2D pitch standards and image processing," App. Phys. A, Vol .66, pp. S847-852, 1998.
6. Gonda, S., Doi, T., Kurosawa, T., Tanimura, Y., Hisata, N., Yamagishi, T., Fujimoto, H. and Yukawa, H., "Real-time, interferometrically measuring atomic force microscope for direct calibration of standards," Rev. Sci. Instrum, Vol. 70, No. 8, pp. 3362-3368, 1999.
7. Gonda, S., Doi, T., Kurosawa, T., Tanimura, Y., Hisata, N., Yamagishi, T., Fujimoto, H. and Yukawa, H., "Accurate topographic images using a measuring atomic force microscope," App. Surf. Sci, Vol. 144-145, pp. 505-509, 1999.
8. http://www.bipm.org
9. Misumi, I., Gonda, S., Kurosawa, T., Takamasu, K.,"Uncertainty in pitch measurements of one-dimensional grating standards using a nanometrological atomic force microscope," Measurement Science and Technology, Vol. 14, No. 4, pp. 463 -471, 2003.
10. Data Sheet of the PSI^{TM} for 145 nm pitch standard sample.
11. ISO, BIPM, IEC, IFCC, ISO, IUPC, IUPAP, OIML, "Guide to the Expression of Uncertainty in Measurement," 1993.
12. Edlen, B., "The refractive index of air," Metrologia, Vol. 2, No. 2, pp. 71-80, 1966.
13. www.asmicro.com