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Method for Determining the Angle in Two Dimension Nanoscale: Pitch Grating

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A two-dimensional (2D) grating is useful for calibrating the accuracy of an electron microscope and atomic force microscope (AFM). An inter laboratory comparison has been carried out for measuring pitches and angles of 2D gratings with 292 and 1000 nm pitches using both AFM and an optical diffractometer (OD). The grating angle at the 292 nm pitch size was obtained at some of the laboratories by the conventional OD method. However, they could not measure the grating angle when the grating pitch was smaller than $(\lambda/2) \times \sqrt{2}$, where λ denotes the laser wavelength. We propose a diffraction angle rotation method of grating angle measurements. Using a precision rotary table along with diffractive light, we accurately measure a 2D grating angle for any pitch size larger than $\lambda/2$. © 2011 The Japan Society of Applied Physics

1. Introduction

A two-dimensional (2D) grating is commonly used to calibrate the accuracy of the x–y plane in scanning electron microscopy (SEM), and atomic force microscopy (AFM). Several studies have been reported on the inspection method used for the 2D grating.[1–3] An inter laboratory comparison, NANO 5, was carried out in 2005 for measuring pitches and angles of 2D gratings with 292 and 1000 nm pitches, respectively, as shown in Fig. 1. The compared items include (1) the average pitch p_x of columns, (2) the average pitch p_y of rows, and (3) the average angle α in the anti clockwise direction between the direction along rows and the direction along columns.

Several national metrology institutes developed optical diffractometers (ODs)[4–7] and metrological scanning probe microscopes (SPMs)[8–10] in the comparison. The inter laboratory comparison result has been reported.[11] Several studies have been reported on inspection methods for the 2D grating. Buhr *et al.*[12] presented the pitch and orthogonality of 2D gratings that had been calibrated using a multi-wavelength OD method. Kim *et al.*[13] described the pitch and orthogonality of 2D gratings calibration using a metrology atomic force microscope (MAFM) and an OD method. They used a mathematical model to calculate the 2D grating angle of the OD method. However, in the inter laboratory comparison, some laboratories using a 543 nm laser in the conventional OD method could not measure the 2D grating angle with 292 nm pitch,[11] since they used pitch sizes p_x, p_y, and p_{xy} to measure the angle in the 2D grating, in which the diagonal pitch p_{xy} is smaller than the diffraction limit.

We propose a diffraction angle rotation (DAR) method for pitch sizes larger than $\lambda/2$. Furthermore, our original homemade MAFM and OD methods are used in this study to measure the angles of 2D gratings with pitches of 292, 700, and 3000 nm. Measurements by the OD, MAFM, and DAR methods were obtained, and expanded uncertainties are presented here with confidence levels of 95%.

2. Mathematic Model

The literature[12,13] provides a mathematical formula with grating angle calculation to simulate scanning images, as shown in Fig. 2. Employing the law of cosines leads to

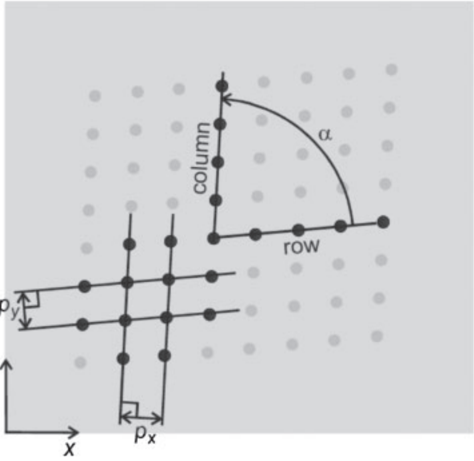

Fig. 1. 2D gratings with average pitches p_x, p_y, and angle α. [Sample figure adapted from technical protocol for NANO5 (2005).]

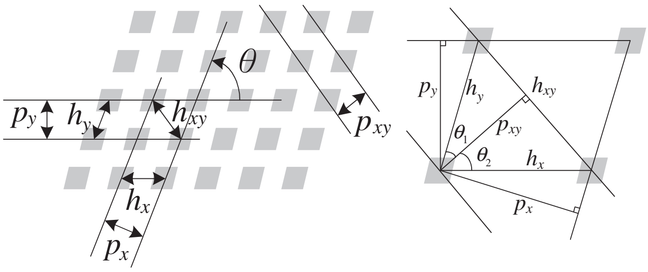

Fig. 2. Schematic and measurands of 2D grating.

$$\cos\theta = \frac{h_x^2 + h_y^2 - h_{xy}^2}{2h_xh_y} \tag{1}$$

and

$$\begin{aligned} \theta &= \theta_1 + \theta_2, \\ p_x &= h_x \sin\theta = h_{xy}\cos\theta_1, \\ p_y &= h_y \sin\theta = h_{xy}\cos\theta_2, \\ p_{xy} &= h_x \cos\theta_2 = h_y\cos\theta_1. \end{aligned} \tag{2}$$

The orthogonality of 2D the grating, which can be calculated by measuring three pitch sizes, is expressed by

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$$
\begin{aligned}
\cos\theta &= \frac{h_x^2 + h_y^2 - h_{xy}^2}{2h_x h_y} \\
&= \frac{\left(\dfrac{p_x}{\sin\theta}\right)^2 + \left(\dfrac{p_y}{\sin\theta}\right)^2 - \left(\dfrac{p_x}{\cos\theta_1}\right)^2}{2\dfrac{p_x}{\sin\theta}\dfrac{p_y}{\sin\theta}} \\
&= \frac{p_x^2 + p_y^2 - \left(\dfrac{\sin\theta}{\cos\theta_1}\right)^2 p_x^2}{2p_x p_y} \qquad (3) \\
&= \frac{p_x^2 + p_y^2 - \left(\dfrac{p_y/h_y}{p_{xy}/h_y}\right)^2 p_x^2}{2p_x p_y} \\
&= \frac{p_x^2 + p_y^2 - \dfrac{p_x^2 p_y^2}{p_{xy}^2}}{2p_x p_y},
\end{aligned}
$$

where p_x is the average pitch along the x-axis, p_y is the average pitch along the y-axis, and p_{xy} denotes the average pitch along the diagonal. We apply eq. (3) to obtain the angle in a 2D grating using both MAFM and OD.

To exemplify, a conventional OD with 543 nm laser wavelength is used to measure a grating where $p_x = p_y = 292$ nm. According to Fig. 2, measured pitch p_{xy} should be rotated 45 degrees relative to the p_x orientation. Thus, the diagonal pitch p_{xy} is $(292\,\text{nm}/2) \times \sqrt{2} = 206.5$ nm, which is smaller than the diffraction limit of a wavelength of 543 nm. Thus, the conventional OD method cannot be used to measure pitches smaller than $(\lambda/2) \times \sqrt{2}$.

3. Measurement Method and Experiments

We propose a DAR method for calibrating the 2D grating angle. In order to validate the DAR method, both high-resolution MAFM and OD methods are used to measure angles in 2D gratings with pitches of 292, 700, and 3000 nm. The 2D gratings with pitches of 292 and 700 nm are made by Advanced Surface Microscopy (Model 2D300 and 2D 700, respectively), using silicon wafer substrates coated with polymer material. The 2D grating with a pitch of 3000 nm is made by VLSI (Model STR3-1800P), using silicon dioxide coated with platinum.

3.1 MAFM method

AFM is a powerful instrument for calibrating pitch dimensions in gratings.[14–17] As shown in Fig. 3, The MAFM system consists of a cantilever from the Quesant atomic force microscope, a flexure stage made by Physik Instrument for active error compensation, and two laser interferometers made by SIOS Meßtechnik along x- and y-axes. The AFM head and the laser interferometers are fixed on a super-Invar metrology frame. A 2D grating is arranged on the same plane as the X and Y laser interferometers, and the AFM tip is located at the intersection of lines extended from the X and Y interferometers, in which the error caused by Abbe offset can be neglected. The MAFM system is installed inside a thermostat maintained at 20 ± 0.1 °C. To carry out the proposed measurement method, the measurement area is $10 \times p$, where p is the average pitch. For example, the size of $30 \times 30\,\mu\text{m}^2$ and 512×512 steps are used to measure the 3 μm pitch size in the 2D grating; the measurement image is shown in Fig. 4. The values of p_x, p_y, and p_{xy} are substituted into eq. (3), to obtain the 2D grating angle. The standard uncertainty and the measurement results for the MAFM method are summarized in Table I.

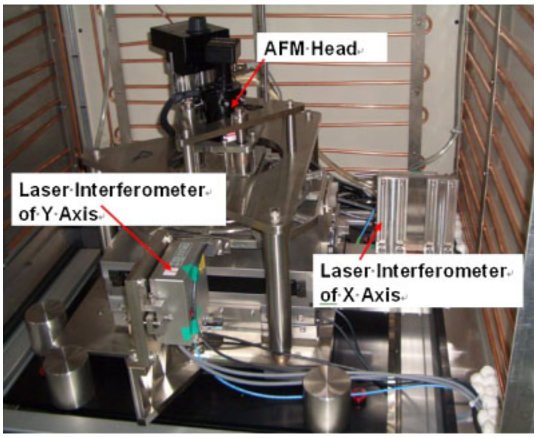


Fig. 3. (Color online) Metrology atomic force microscope system.

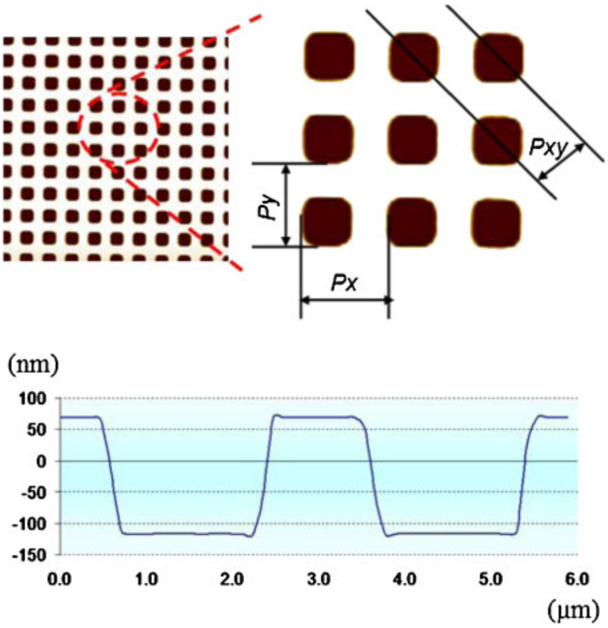


Fig. 4. (Color online) Measured image of 2D grating.

3.2 OD method

A conventional OD provides superior measurement accuracy.[18,19] Most OD methods are based on the Littrow configuration[20] where the diffraction beam coincides with the incident laser beam, although various designs have been presented for measuring the grating pitch. The pitch size is calculated from the laser wavelength and diffraction angle, and the minimum measurable grating pitch is about one-half of the laser wavelength. For instance, a conventional OD method with a 543 nm laser cannot be used to measure a grating pitch smaller than 272 nm. In the Littrow configuration, the grating equation used to calculate the pitch size is written as[21–23]

Table I. Uncertainty budget for 2D700 angle calibration by MAFM Method.

Input quantity	Uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution (nm)
x-pitch p_x	0.097	Normal	1	0.097
y-pitch p_y	0.063	Normal	1	0.063
Diagonal p_{xy}	0.137	Normal	1	0.137
Combined uncertainty				0.180

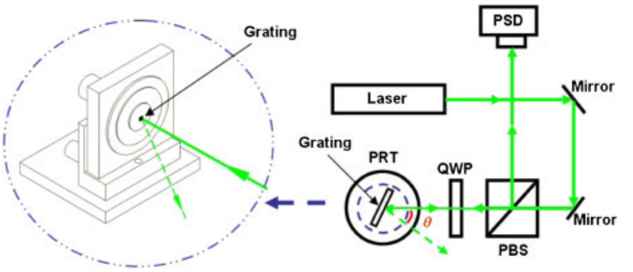


Fig. 5. (Color online) Experimental setup of 2D grating.

$$P = \frac{m\lambda}{2n\sin\theta}, \tag{4}$$

where P denotes the grating pitch, m is the diffraction order, n is the refractive index of air, λ is the wavelength of the laser, and θ is the angle of the diffraction beam.

In this study, an OD method is used to measure 2D grating angles with pitch sizes of 292, 700, and 3000 nm using a wavelength of 543 nm. A sketch schematic of the OD method is shown in Fig. 5. The setup consists of a He–Ne laser, precision rotary table (PRT; Aeotech ADR 240), position-sensitive detector (PSD), a polarized beam splitter (PBS), a quarter-wave plate (QWP), and some optics. In order to establish the traceability to SI units for the OD method, the laser wavelength is traced to the wavelength meter. The wavelength is 543.5165 nm, and the wavelength meter is calibrated with the iodine-stabilized He–Ne laser at the National Metrology Institute (NMI). The angle measurement of the PRT is traced to a standard polygon at NMI. The laser beam is first aligned. It is incident on and perpendicular to the measurement surface of the grating, and must coincide with the zero-order diffraction beam reflected from the grating, according to the Littrow configuration. Angles are thus measured and recorded using the PRT and PSD. Values of p_x, p_y, and p_{xy} are substituted into eq. (3), to obtain the 2D grating angle. The standard uncertainty and measurement results for the OD method are summarized in Table II.

3.3 DAR method

In the inter laboratory comparison, some laboratories adopting the conventional OD method could not measure the angle in the 2D grating with 292 nm pitch. They used a mathematical model to calculate the 2D grating angle in the OD method, since they used pitch sizes p_x, p_y, and p_{xy} to calculate the angle in the 2D grating, which cannot be measured using OD if pitches lie between $\lambda/2$ and $(\lambda/2) \times \sqrt{2}$. Hence, for the sake of pitch sizes larger than $\lambda/2$, we propose the DAR method. The DAR method consists of a He–Ne laser, a sample stage, a PRT, and a PSD. In this method, 292, 700, and 3000 nm gratings are calibrated using light emitted from a He–Ne laser at a wavelength of 543 nm. The experimental setup of the DAR method is shown in Fig. 6.

Table II. Uncertainty budget for 2D700 angle calibration by OD Method.

Input quantity	Uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution (nm)
Measured	0.0038	Normal	1	0.0038
Rotation	0.0003	Normal	1	0.0003
PSD	0.00087	Rectangular	1	0.0005
Alignment	0.00139	Rectangular	1	0.0008
Combined uncertainty				0.004

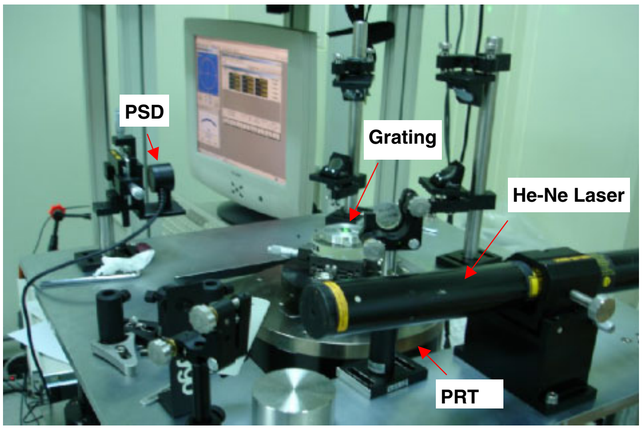
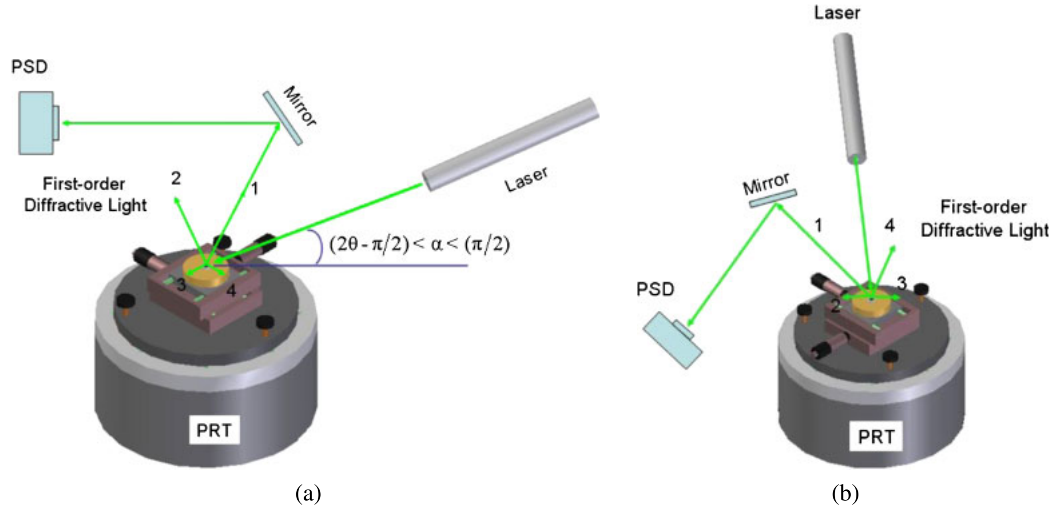


Fig. 6. (Color online) Diffraction angle rotation system.

A 2D grating is fixed on a sample stage, and the rotation axis of the PRT passes through the normal direction of the grating surface, as shown in Fig. 7. A laser beam is incident with an angle α on the surface of the 2D grating at $(2\theta - \pi/2) < \alpha < (\pi/2)$ with respect to the rotation axis of the PRT, where θ is based on the Littrow configuration and is obtained from eq. (4). Under conditions of $\lambda = 543$ nm and $p = 292$ nm in this experiment, $\theta = 70°$ can be obtained. Four first-order diffraction beams are obtained from the 2D grating at 0, 90, 180, and 270°; namely, diffractive light Nos. 1 to 4 from p_x, p_y. According to Fig. 7, diffractive light No. 1 is reflected by the mirror and enters a PSD. The PRT is rotated 180° to let diffractive light No. 3 enter the PSD. The sample stage is adjusted so that two diffractive lights, 0° and 180°, can secure the same zero position of the PSD. By using the PRT and PSD positions, the grating angles θ and $\pi + \theta$ corresponding to diffractive light Nos. 2 and 4 can also be obtained. Finally, the standard uncertainty and the measurement results for the DAR method are shown in Table III.

4. Measurement Results

In this study, we carried out the DAR, MAFM, and conventional OD methods to measure 2D grating angles of 2D292, 2D700, and 2D3000 gratings. Comparing the results from OD and MAFM methods with those of the proposed method, one can immediately recognize that the proposed method is the best. Measurement results and expanded uncertainties of these methods are summarized in Table IV;



(a) (b)

Fig. 7. (Color online) Experimental setup of the DAR method: (a) configuration of the system and (b) another view of the whole system.

Table III. Uncertainty budget for 2D700 angle calibration by DAR Method.

Input quantity	Uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution (nm)
Measured	0.0036	Normal	1	0.0038
Rotation	0.0003	Normal	1	0.0003
PSD	0.00087	Rectangular	1	0.0005
Alignment	0.00139	Rectangular	1	0.0008
Combined uncertainty				0.004

Table IV. Measurement results and standard uncertainties for 2D grating angle.

2D grating		Pitch sizes		
		292 nm α (90°)	700 nm α (90°)	3000 nm α (90°)
Measurement results (deg)	OD	—	90.233	90.015
	MAFM	90.546	90.191	90.037
	DAR	90.550	90.236	90.011
Expanded uncertainty[a)] (deg)	OD	—	0.008	0.036
	MAFM	0.562	0.360	0.214
	DAR	0.010	0.008	0.008

a) $k = 2$, at 95% confidence

the confidence level is 95% and coverage factor $k = 2$.24) Measurement results of the DAR method are found to be in agreement with those of both MAFM and OD methods.

5. Conclusions

The proposed DAR method has merits such as simple optical configuration, high measurement accuracy, and rapid measurement. We demonstrated the feasibility of measuring 2D grating angles by the DAR method. Comparing Table II with Table III, one can notice that the proposed method can resolve smaller pitches between $(\lambda/2) \times \sqrt{2}$ and $\lambda/2$. The conventional OD method cannot be using to measure the 2D grating angle with pitch size smaller than $(\lambda/2) \times \sqrt{2}$, although it enables easy measure most of large pitches. This can be improved if another light source with shorter wavelength is used. In addition, although MAFM is a powerful instrument for calibrating the grating pitch, according to Table IV, its measurement accuracy is not satisfactory for calculating 2D grating angles.

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