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Uncertainty Estimation in Intelligent Coordinate and Profile Measurement

Kiyoshi Takamasu[1, a], Satoru Takahashi[1, b] and Xin Chen[2, c]

[1]Department of Precision Engineering, The University of Tokyo,
7-3-1 Hongo, Bunkyoku, Tokyo, 113-8656 JAPAN

[2]Department of Information Measuring Technology and Instrument, Shanghai Jiao Tong University,
800 Dongchuan Road, Shanghai, 200240, CHINA

[a]takamasu@pe.t.u-tokyo.ac.jp, [b]takahashi@nanolab.t.u-tokyo.ac.jp, [c]xchen.ie@sjtu.edu.cn

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Abstract. The uncertainty estimation of coordinate and profile measurement is essential for accurate measurement and establishment of traceability. We proposed an uncertainty propagation method to estimate the uncertainty of coordinate and profile measurement. In this article, the multi sensor algorithm with uncertainty estimation method is described for the profile measurement. Additionally, two examples of multi sensor method are introduced. According to the simulation results of assessing uncertainty and the experimental results, the validity of the method was confirmed.

Introduction

The uncertainty estimation of coordinate and profile measurement is essential for accurate measurement and establishment of traceability [1-3]. We proposed an uncertainty propagation method to estimate the uncertainty of coordinate and profile measurement [4, 5]. In this article, the uncertainty estimation method is applied for the multi sensors profile measurement with error separation. According to the amount and the configuration of the sensors, the multi sensor algorithms are applied so that the topography can be reconstructed accurately from the measurement values. The existing algorithm is mathematically exact in the absence of the random and systematic errors and is stable when the random error is considered. We applied the multi sensor method for the profile measurement in semiconductor industry. In this article, the multi sensor algorithm with uncertainty estimation method is described for the profile measurement. Additionally, two examples of multi sensor method are introduced. According to the simulation results of assessing uncertainty and the experimental results, the validity of the method was confirmed.

Error Separation Method by Multi Sensor Method for Profile Measurement

Least Squares Solution for Multi Sensor Method. Scanning topography measurements using systems of multi sensor is theoretically described [4]. The topography was reconstructed by the application of the least squares analysis, and the uncertainty associated with the reconstructed topography is derived [6, 7]. Combining the error separation approach with the multi sensor system, we developed the model with the multi sensor and autocollimator shown in Fig. 1. The sensor system consists of M number of displacement sensors aligned along the scanning direction, the x-direction. A mirror is attached to the moving stage, and an autocollimator is used for the additional angular measurements of the stage. While the sample is moved to touch the multi sensors by the moving stage, from the autocollimator and the displacement sensors in each of its positions, we have the model relation as Eq. (1).

$$\begin{aligned} y_j(x_n) &= f(x_n + D_j) + e_y(x_n) + D_j \cdot e_p(x_n) + u_j, \\ y_a(x_n) &= e_p(x_n) + u_a \qquad (j = 1, \cdots, M, \quad n = 1, \cdots, N) \end{aligned} \tag{1}$$

where x_n is the horizontal position of the stage, $y_j(x_n)$ denotes the distance of the jth sensor at the nth position of the scanning system from the topography. The distance of the sensor $y_j(x_n)$ is composed of the unknown systematic sensor errors u_j, the scanning stage errors $e_y(x_n)$ and $e_p(x_n)$, and the topography $f(x_n + D_j)$. D_j is the distance of the jth sensor to the 1st sensor, and D_j should be integral multiples of s, which is the scanning interval. The multiple cantilevers are moved by scanning interval s on each measurement. The measured angle $y_a(x_n)$ is the angle of the moving part of the scanning stage measured by the autocollimator in each of its positions. The measured angle $y_a(x_n)$ is composed of the jth systematic sensor error of the autocollimator u_a and the pitching error of the sensors $e_p(x_n)$. Here, we define some symbols to make the model easier as Eq. (2).

$$\begin{aligned} & e_1(x_n) = e_y(x_n) + u_1, \\ & e_2(x_n) = e_p(x_n) + u_a, \qquad (n = 1, \cdots, N_S) \\ & c_j = u_j - u_1 - D_j u_a, \qquad (j = 1, \cdots, M) \end{aligned} \tag{2}$$

The expression $f(x_1),..., f(x_N−2)$ denotes the first $N−2$ topography values. Eqs. (1) and (2) are compactly written as Eq. (3), where **Y** and **X** denote the measuring vector and unknown vector involving topographies and system error, respectively.

$$\begin{aligned} & \mathbf{Y} = \mathbf{AX}, \\ & \mathbf{Y} = \left[y_1(x_1) \cdots y_M(x_1), y_1(x_2) \cdots y_M(x_{N_S}), y_a(x_1) \cdots y_a(x_{N_S}) \right]^{\mathrm{T}}, \\ & \mathbf{X} = \left[f(x_1) \cdots f(x_{N-2}), e_1(x_1) \cdots e_1(x_{N_S}), e_2(x_2) \cdots e_2(x_{N_S}), c_2 \cdots c_M \right] \end{aligned} \tag{3}$$

When **A** has satisfied the condition for reconstructing the topography by the application of the least squares method, we can achieve a separation in the presence of the considered scanning stage and systematic sensor errors. In addition, uncertainty associated with the reconstructed topography can be derived.

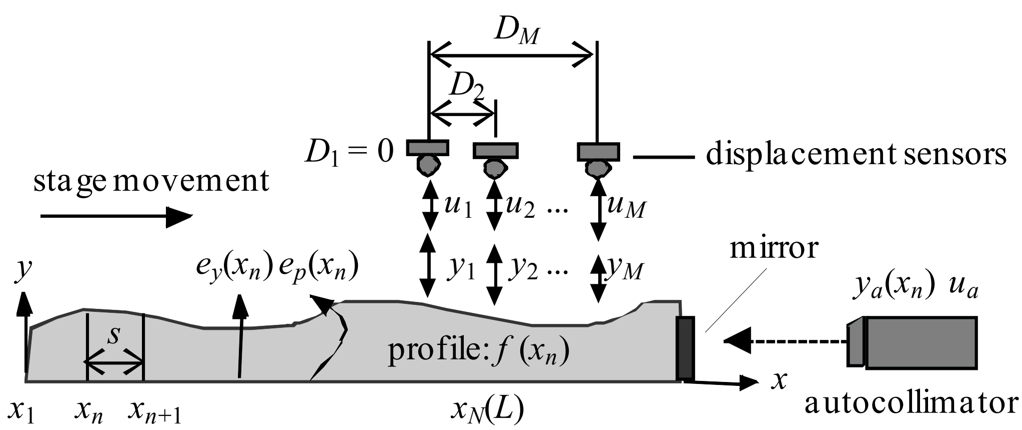

Figure 1. Scanning system of coupled distance sensors together with an autocollimator as an additional angle-measuring device. A mirror is attached to the moving stage.

Uncertainty Estimation for Multi Sensor Method. The diagonal matrix **S** can be given by random measurement errors. Here, on the basis of the measurement points, the dispersion of random errors can be set by the standard deviation of the distance sensors and standard deviation of the autocollimator. The matrix $\mathbf{S}_p$ can give the associated uncertainty as Eq. (4). Then, the uncertainty in every measurement point $u_f(n)$ can be obtained from matrix $\mathbf{S}_p$. We applied the multi sensor method to the profile measurements in semiconductor industry. In this article, two examples of multi sensor method are described.

$$\mathbf{S}_p = \begin{pmatrix} r_{11} & \cdots & r_{1Q} \\ \vdots & \ddots & \vdots \\ r_{Q1} & \cdots & r_{QQ} \end{pmatrix} = (\mathbf{A}^{\mathrm{T}}\mathbf{S}^{-1}\mathbf{A})^{-1} \tag{4}$$

Example 1: Multi-Ball Cantilever System [6]

Construction of the Multi-Ball Cantilever System. We constructed a multi-ball cantilever system to measure the surface of resist film, as shown in Fig. 2 (a). The white light interferometer used for the experimental studies was a ZYGO NewView6300, which can detect height information with a height resolution of 0.1 nm. In this system, an XY stage and a Z stage move the position of sample. The multi-ball cantilever is a NANOWORLD Arrow TL8-50, as shown in Fig. 2 (b), which used 8 cantilevers spaced 250 μm apart. Each cantilever held a ball stylus 10.9 μm in diameter. According to error separation approach, the autocollimator is set in the multi-ball cantilever system, and the autocollimator resolution is 1 arc-sec.

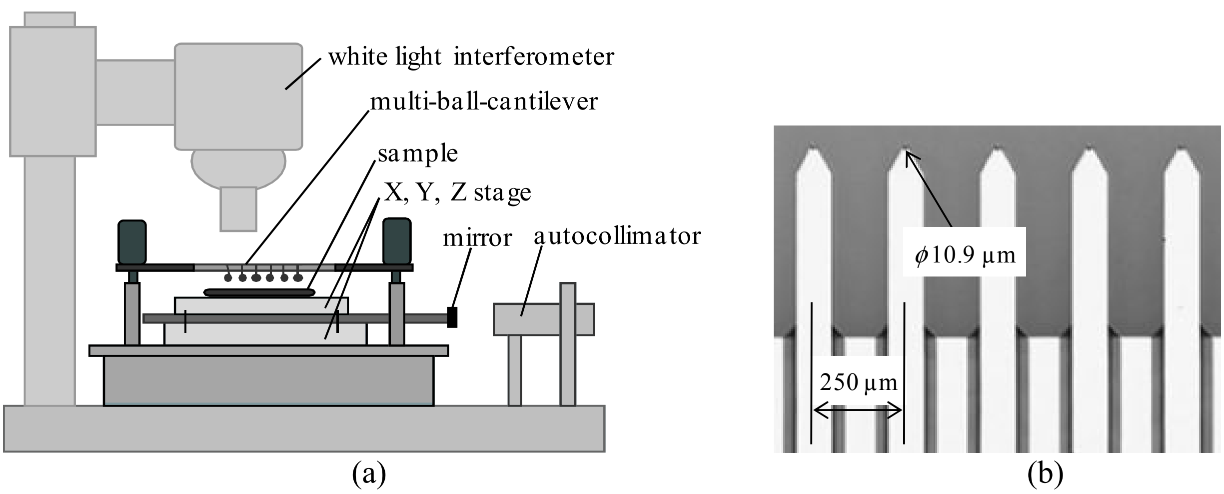

Figure 2. (a) Construction of a multi-ball cantilever system with an autocollimator. (b) Multi-ball cantilever (NANOWORLD Arrow TL8-50).

Measurement of Profile of Resist Thin Film. We measured profile of resist thin film (Fig. 3) by observing 6 cantilevers of the multi-ball cantilever system. The scanning interval s in this measurement was 250 μm. Fig. 4 shows the position of the 6 cantilevers measured by the white light interferometer in 41 scans over 11 mm.

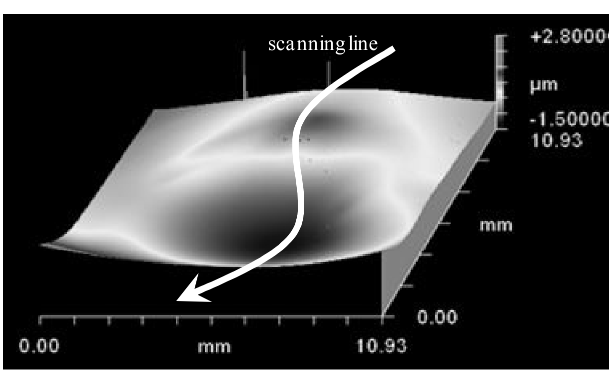

Figure 3. Resist profile scanning over 11 mm.

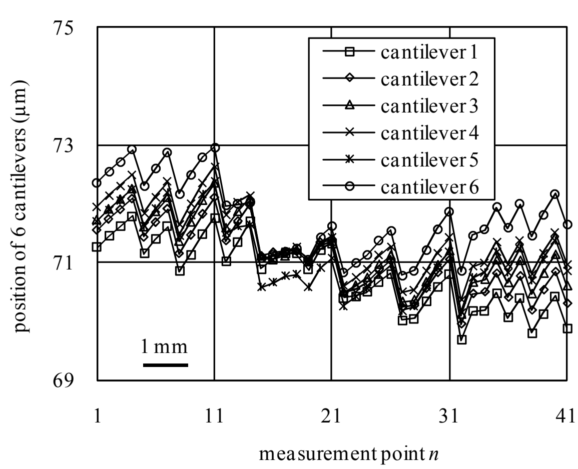

Figure 4. Positions of 6 cantilevers on 41 scans.

Error Separation and Uncertainty Estimation. Fig. 5 shows the results of four measurements using 6 cantilevers by error separation method from the positions of cantilevers in Fig. 4. Fig. 6 shows the relation of the expanded uncertainty and the bias, which is the gap between the real profile and the average measurement value by 6 cantilevers. In this experiment, we realized a reconstruction of the shape with 29.7nm as the average standard deviation. This experimental standard deviation is near to the theory uncertainty when the standard deviation condition on the interferometer and autocollimator is set to 30 nm and 3 arc-sec, respectively.

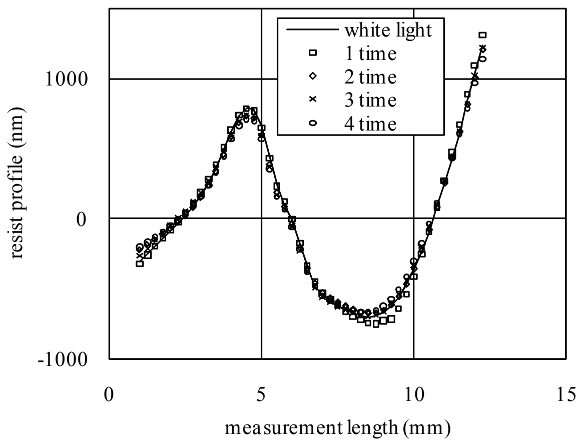

Figure 5. Calculated resist profile from four measurements by 6 cantilevers.

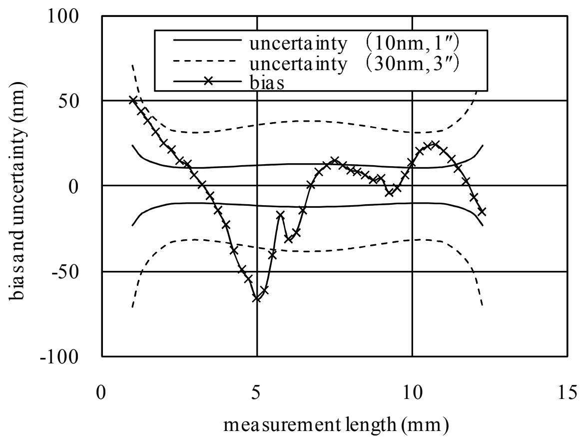

Figure 6. Expanded uncertainty and bias between real profile and average measurement value.

Example 2: Calibration of Planar Linear Motor [7]

Planar Linear Motor System. Planar linear motor is a kind of 2D precision positioning stage, which is different from the usual XY stage and is composed of multiple linear motors arranged orthogonally in a same layer. It is a general way to employ 3 axis laser interferometers and square-mirror as the positioning sensor of Sawyer planar linear motor (Fig. 6) for applications with nano meter order resolution. A geometrical calibration method is proposed according to the errors affecting the measurement of the laser interferometer, such as the profiles of the two plane mirrors and the flatness of platen. The method is easy to perform on the user side and useful to evaluate the single geometrical motion error without the standard square-gauge or the cross grid-scale. The profiles of the X and Y axis plane mirrors are measured by the 2 point method (Fig. 7) with yawing compensation is applied to both of the mirrors.

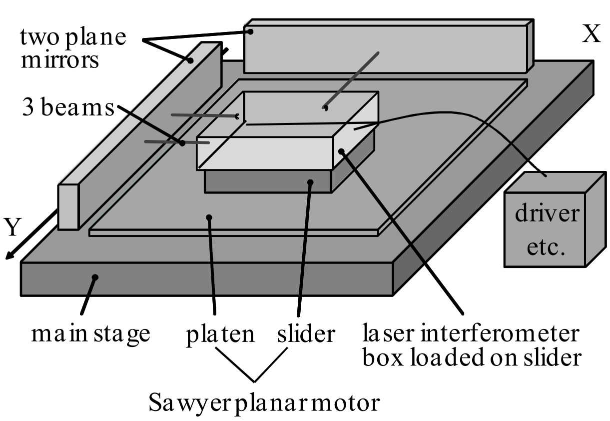

Figure 6. Sawyer planar motor system with three laser interferometers, slide size 220 mm × 220 mm.

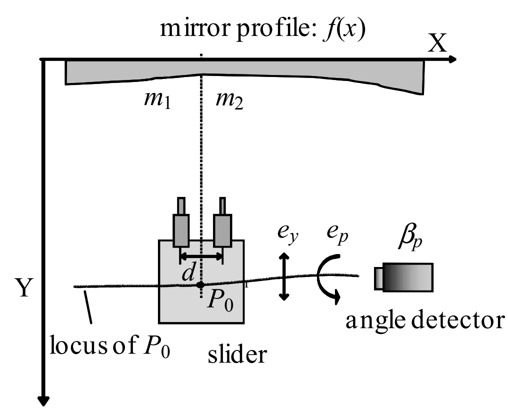

Figure 7. 2 point method to measure profile of X axis mirror.

Error Separation Method. The 2 point method (Fig. 7) is applied to measure the profile of X axis mirror. Two displacement sensors were LHG-110 (resolution: 10 nm) and an angle detector was laser interferometer (ML10) with angle optical system (resolution: 0.01 arc-sec). The distance *d* is 25 mm and the planar motor is scanned in 300 mm range by open loop mode. The yawing variance is approximately 50 arc-sec. Fig. 8 shows the five iteration measurements of X axis mirror using 2 point method. The mirror has approximately 1.7 μm form deviation and measuring uncertainty (standard deviation) is 58 nm. The theoretically estimation uncertainty is good agreement with experimental uncertainty. Fig. 9 shows comparison between the profiles measured by 2 point method and tangent method. The profiles are good agreement with maximum difference of 0.1 μm.

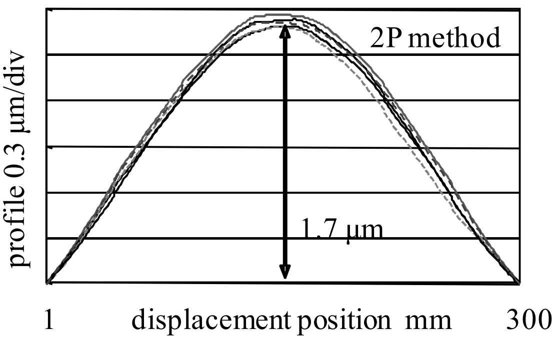

Figure 8. X axis mirror profile calculated by 2 point method.

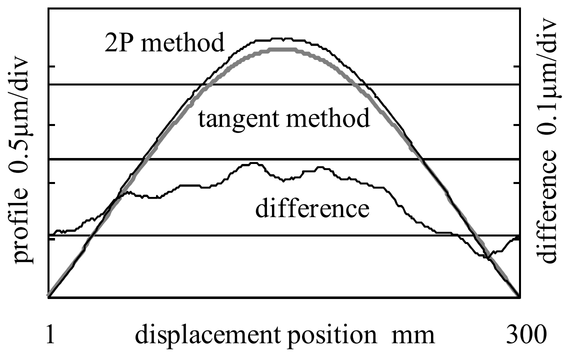

Figure 9. Comparison of X axis mirror profile between tangent method and 2 point method.

Summary

The uncertainty estimation method is key technology in accurate coordinate and profile measurements. The least squares solution and error propagation method are theoretically formulated for the multi sensor method of profile measurement. Additionally, two examples of multi sensor method are introduced. According to the simulation results of assessing uncertainty and the experimental results, the validity of the method was confirmed.

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