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Profile measurement of a wide-area resist surface using a multi-ball cantilever system

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ABSTRACT

In the semiconductor industry, a device that can measure the surface profile of thin film like photoresist with high accuracy and high speed is needed. Since the surface of photoresist is very smooth and deformable, a device is required that will measure vertically with nanometer resolution and not damage the film during the measurement. We developed an apparatus using a multi-ball cantilever and white light interferometer to measure the surface profile of thin film. However, this system, as assessed with a scanning method, suffers from the presence of a moving stage and systematic sensor errors. Therefore, this paper describes an approach using a multi-ball cantilever as coupled distance sensors together with an autocollimator as an additional angle measuring device, which has the potential for self-calibration of a multi-ball cantilever. Using this method, we constructed an experimental apparatus and made measurements on resist film. The results demonstrated the feasibility of the constructed multi-ball cantilever system with the autocollimator for measuring thin film with high accuracy.

1. Introduction

As a result of the demand for high efficiency in the semiconductor manufacturing industry, nanometrology is rapidly gaining importance. Photoresist on a wafer is a soft thin film about 500 nm thick and is currently under development [1]. We wanted to develop an instrument that can measure this thin film with a vertical resolution of 10 nm within the horizontal range of tens of millimeters. Usually, we use a light scanning method to measure a surface profile quickly and with high accuracy without contact, e.g. a con-focal microscope and a white light interferometer. Here, the problem is that photoresist is less than 500 nm thick. When we measure it with the light scanning method directly, multiple interferences and reflections of the thin film obstruct the profile measurement with optical noise, making correct measurement impossible. As another approach, atomic force microscopy (AFM) can be used to take measurements by a probe with high accuracy. However, if the measured object is softer than the AFM stylus tip, the tip may deform it during the measurement, and the speed is limited because AFM is used in micro-area measurements. Since the photoresist surface is deformable and smooth [2], the measurement device must not damage it during the measurement, and the resolution in the horizontal direction must be in tens of micrometers.

In this research, we hoped to measure thin film by using a contact method just like AFM, combining optical measurement (white light interferometer) and mechanical contact (multi-ball cantilever). To solve the problems just described, we constructed an apparatus that covers a wide area at high speed. Each cantilever has a ball stylus with a diameter that does not plastically deform the measured surfaces [3].

Fig. 1 shows the multi-ball cantilever system concept. In measurements, the ball probe is touched to the sample, and then the upper surface of the probe is measured by a white light interferometer at high resolution. Therefore, the surface profile of the sample is measured without multiple interference of thin film and it is possible to measure a large area at high speed by scanning the multiple probe cantilevers with a white light interferometer to achieve the demand for a resist surface measurement. During measurement, the multi-ball cantilever is fixed, and the sample is moved to contact the cantilevers. The profiles of touched cantilevers are scanned by the white light interferometer.

2. Error separation method

Scanning topography measurements using systems of multiple cantilevers suffer mainly from the presence of scanning stage and systematic sensor errors. In this research, we aimed to solve these problems by a kind of error separation approach, which uses multiple cantilevers as coupled distance sensors together with an autocollimator as an additional angle-measuring device,

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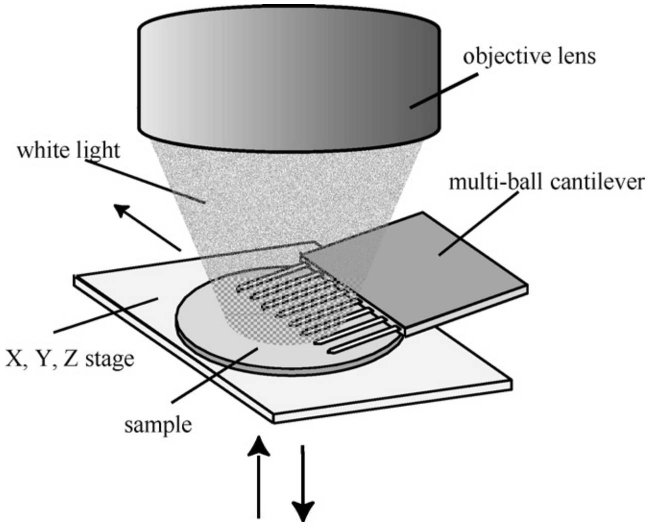

Fig. 1. The multi-ball cantilever system concept.

as proposed by Elster and Weingärtner [4]. The topography was reconstructed by the application of the least-squares analysis, and the uncertainty associated with the reconstructed topography is derived.

Combining the error separation approach with the multi-ball cantilever system, we developed the model with the multi-ball cantilever and autocollimator shown in Fig. 2. The sensor system consists of M number of ball cantilevers aligned along the scanning direction, the x-direction. A mirror is attached to the multi-ball cantilever system, and an autocollimator is used for the additional angular measurements of the moving stage. The autocollimator, the moving stage carrying the sample, and the multi-ball cantilever are rigidly fixed to the table. The systematic error is mainly introduced by the gap between the zero values of multiple sensors based on a certain reference line, which is called the zero-adjustment [5]. We assume that the systematic error includes only the zero-adjustment error. While the sample is moved to touch the multi-ball cantilever by the moving stage, from the autocollimator and the white light interferometer measurements in each of its positions, we have the model relation as Eq. (1).

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

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 there is the existence of $D_1 = 0$. In the analysis, 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).

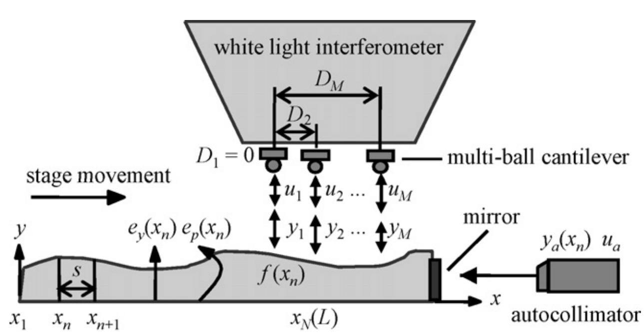

Fig. 2. Scanning system of coupled distance sensors together with an autocollimator as an additional angle-measuring device. A mirror is attached to the moving stage.

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

In Eqs. (1) and (2), there is the relation $N = N_s + M - 1$. N is the number of all measurement points, and N_s are the scanning times. The non-unique straight line will be fixed by posing the additional conditions as Eq. (3).

$$\sum_{n=1}^{N} x_n f(x_n) = \sum_{n=1}^{N} f(x_n) = 0 \tag{3}$$

These conditions imply that the best straight line fit to the resulting topography $f(x_1),\ldots, f(x_N)$ equals the x-axis. The constraints of Eq. (3) can, for instance, be explicitly taken into account by substituting $f(x_{N-1})$ and $f(x_N)$ according to Eq. (4).

$$f(x_{N-1}) = \sum_{n=1}^{N-2} (n - N) f(x_n), \quad f(x_N) = \sum_{n=1}^{N-2} (N - 1 - n) f(x_n) \tag{4}$$

The expression $f(x_1),\ldots, f(x_{N-2})$ denotes the first $N - 2$ topography values. It is easily checked that when using Eq. (4), Eq. (3) is satisfied for all choices of $f(x_1),\ldots, f(x_{N-2})$. Eqs. (1) and (2) are compactly written as Eq. (5), where $\mathbf{Y}$ and $\mathbf{X}$ denote the measuring vector and unknown vector involving topographies and system error, respectively.

$$\begin{aligned} &\mathbf{Y} = \mathbf{AX}, \\ &\mathbf{Y} = [y_1(x_1) \ldots y_M(x_1), y_1(x_2) \ldots y_M(x_{N_S}), y_a(x_1) \ldots y_a(x_{N_S})]^T, \\ &\mathbf{X} = [f(x_1) \ldots f(x_{N-2}), e_1(x_1) \ldots e_1(x_{N_S}), e_2(x_2) \ldots e_2(x_{N_S}), c_2 \ldots c_M] \end{aligned} \tag{5}$$

when $\mathbf{A}$ 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. The diagonal matrix $\mathbf{S}$ can be given by random measurement errors in Eq. (6). Here, on the basis of the measurement points, the dispersion of random errors can be set by the standard deviation of the white light interferometer and standard deviation of the autocollimator. In this system, σ_{y1} to σ_{yM} are standard deviations of measured distances $y_1(x_n)$ to $y_M(x_n)$ by the white light interferometer, and σ_{ya} is the standard deviation of an angle measured by the autocollimator.

$$\mathbf{S} = \begin{pmatrix} \sigma_{y1}^2 & & & & & & & & & \\ & \ddots & & & & & & 0 & & \\ & & \sigma_{yM}^2 & & & & & & & \\ & & & \sigma_{y1}^2 & & & & & & \\ & & & & \ddots & & & & & \\ & & & & & \sigma_{yM}^2 & & & & \\ & & & & & & \sigma_{ya}^2 & & & \\ & & & & & & & \ddots & & \\ & 0 & & & & & & & \sigma_{ya}^2 & \end{pmatrix} \tag{6}$$

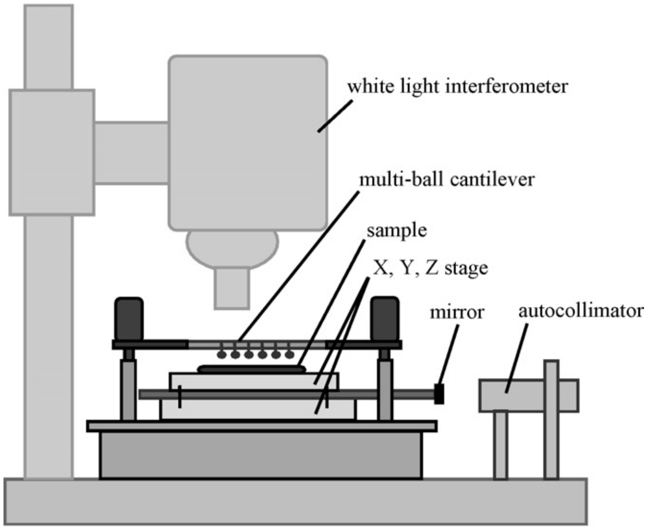

Fig. 3. Construction of a multi-ball cantilever system with an autocollimator.

The matrix $\mathbf{S}_p$ can give the associated uncertainty as Eq. (7). We obtain the following relation: $Q = N - 2 + 2N_S + M - 1$. Then, according to Eqs. (4) and (7), the uncertainty in every measurement point $u_f(n)$ can be obtained as Eq. (8). Note that the uncertainties associated with the reconstructed topography depend neither on the topography itself nor on the scanning stage and systematic sensor errors. The mean uncertainty u_m is obtained as Eq. (9).

$$\mathbf{S}_p = \begin{pmatrix} r_{11} & \cdots & r_{1Q} \\ \vdots & \ddots & \vdots \\ r_{Q1} & \cdots & r_{QQ} \end{pmatrix} = (\mathbf{A}^T\mathbf{S}^{-1}\mathbf{A})^{-1} \tag{7}$$

$$\begin{aligned} u_f^2(n) &= r_{nn}, \quad (n = 1, \ldots, N-2), \\ u_f^2(N-1) &= \sum_{i,j=1}^{N-2} (i-N)(j-N) r_{ij}, \\ u_f^2(N) &= \sum_{i,j=1}^{N-2} (N-1-i)(N-1-j) r_{ij} \end{aligned} \tag{8}$$

$$u_m = \sqrt{\frac{1}{N}\sum_{n=1}^{N} u_f^2(n)} \tag{9}$$

3. Construction of the multi-ball cantilever system

Using our proposal, we constructed a multi-ball cantilever system to measure the surface of resist film, as shown in Figs. 3 and 4. 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 and profile heights ranging from 1 nm to 15,000 μm. As a new feature, the new Film Application software for NewView6300 was used to measure thin film from 1.5 to 50 μm thick. In this system, an XY stage (COMS PT100C-50XY) and a Z stage (PI P-541.TCD) move the position of sample. The resolutions of the XY stage and Z stage are 1 μm and 0.8 nm, respectively. The multi-ball cantilever is a NANOWORLD Arrow TL8-50, as shown in Fig. 4(b) and (c), which used 8 cantilevers spaced 250 μm apart. Each cantilever held a ball stylus 10.9 μm in diameter. The material of the ball was SiB. The spring constant of the cantilever was 0.03 N/m. In the last research, we considered the relationship of stylus size, force and resist by simulation, and we know that this size could not transform the resist [3]. According to the error separation approach, the autocollimator (5LAB HAWK-301HR) is set in the multi-ball cantilever system, and the autocollimator resolution is 1 arcsec.

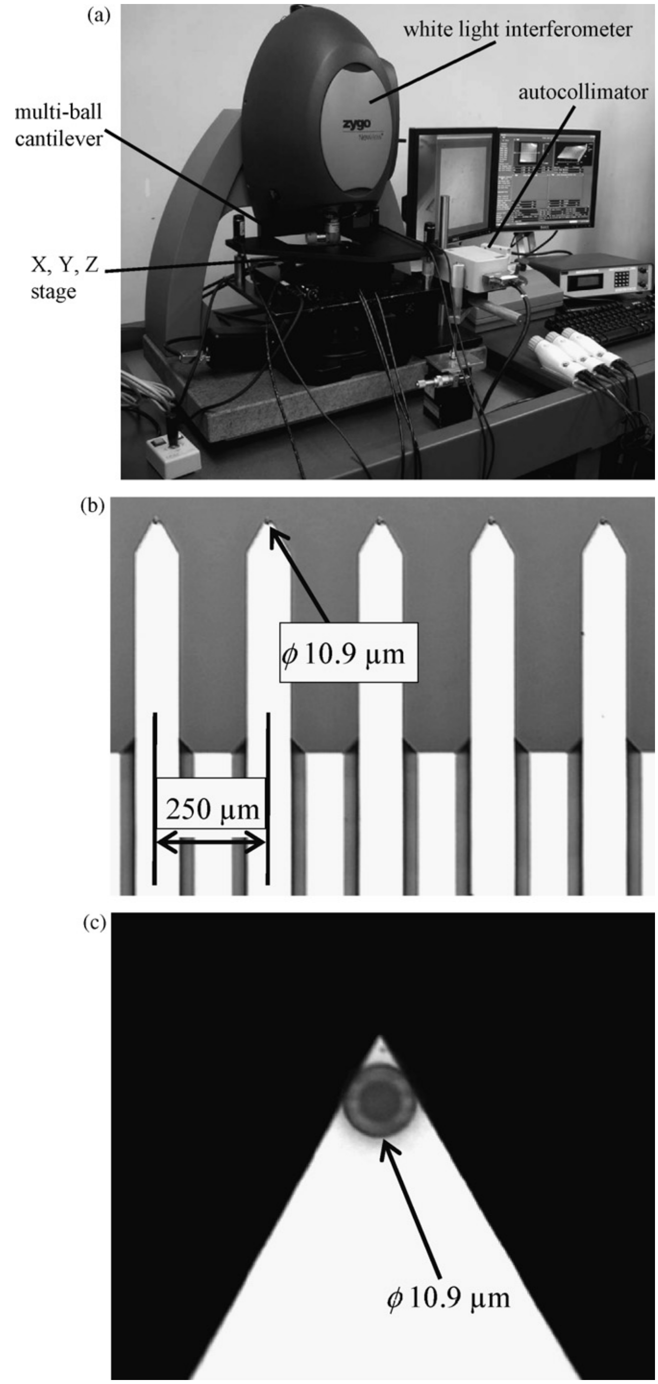

Fig. 4. Photographs of the realized multi-ball cantilever system and the multi-ball cantilever. (a) System construction, (b) multi-ball cantilever and (c) top of the cantilever.

4. Thin film measurement

4.1. Sample of photoresist thin film

To verify the feasibility of the constructed system, we carried out scanning experiments on the resist surface. We measured a resist sample applied to the silicon wafer that was about 25 μm thick.

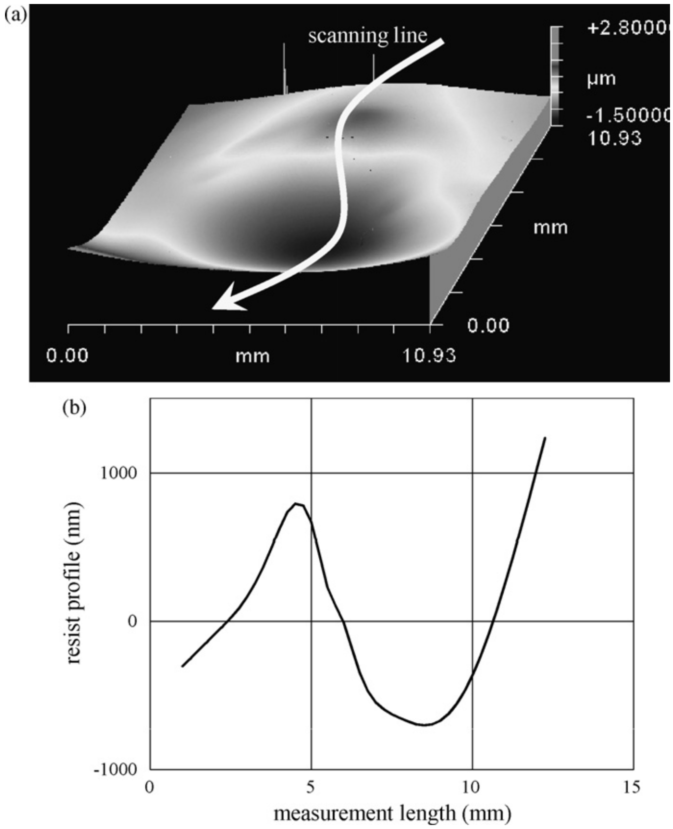

Fig. 5. Resist profile scanning by the film application of NewView6300, with a scanning length of 11.25 mm. (a) 3D image and (b) sectional surface.

Here we derived the resist surface profile as the original profile by the thin film application of NewView6300, which can detect the thickness and surface profiles of thin film from 1.5 to 50 μm thick. Along the scanning line of Fig. 5(a), the profile shown in Fig. 5(b) was obtained. The measurement length is 11.25 mm.

4.2. *Measurement with the multi-ball cantilever system and the feasibility of the error separation method*

We measured resist thin film by observing 6 cantilevers of the multi-ball cantilever system. The scanning interval s in this measurement was 250 μm. Fig. 6 shows the position of the 6 cantilevers

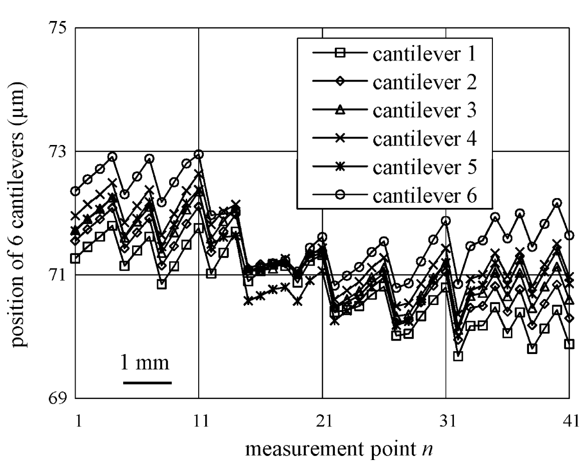

Fig. 6. Position of 6 cantilevers on 41 scans measured by the white light interferometer.

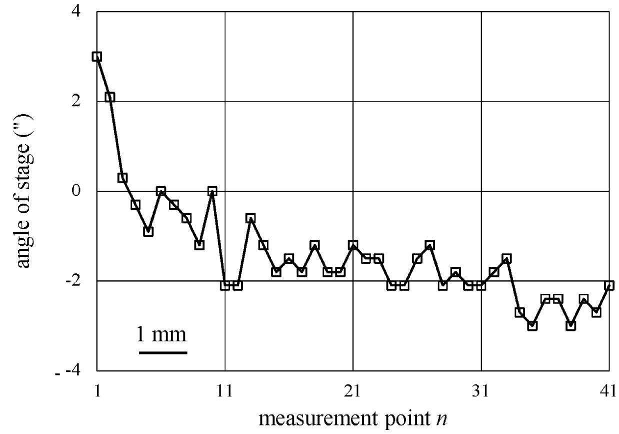

Fig. 7. Angle of the stage on 41 scans measured by the autocollimator.

measured by the white light interferometer in 41 scans, and Fig. 7 is the angle of stage measured by the autocollimator.

To demonstrate the benefit of the additional autocollimator in combination with the proposed system, we analyzed the measurement data with and without the autocollimator. Fig. 8 shows the calculated results using the measurement data of 3 cantilevers. Fig. 8(a) is the profile by NewView6300 and the calculated profile by the normal 3-point method without the autocollimator [5]. According to our analysis, we know the profile cannot be derived under the influence of system error in this scanning measurement. However,

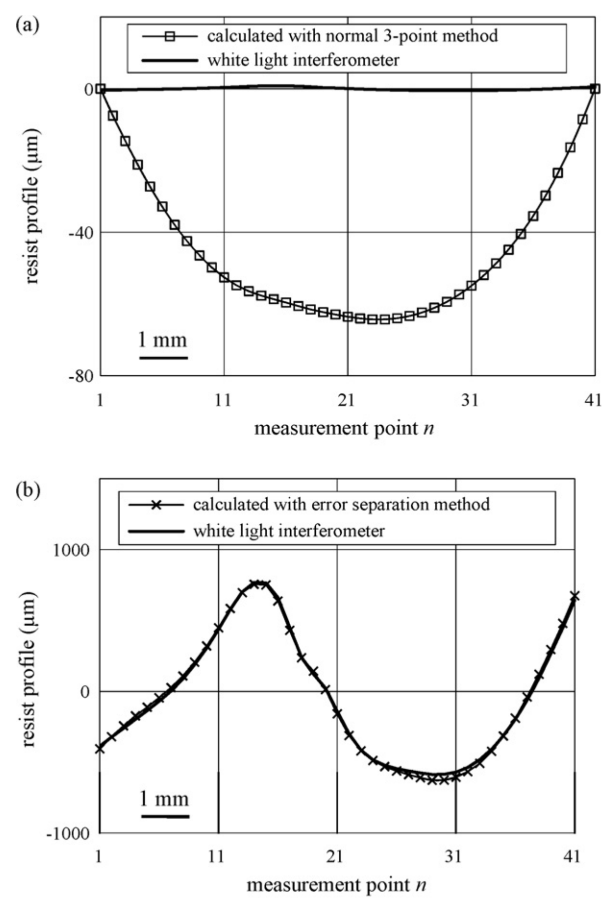

Fig. 8. Calculated results (a) by the normal 3-point method and least-squares with error separation method using an autocollimator and (b) by the least-squares with error separation method with an autocollimator.

Table 1
Distance of cantilevers for 3, 4, 5 and 6 cantilevers measuring conditions

Numbers of cantilevers	Distance of D_j to 1st sensor
3 cantilevers	D = 0, 250, 1250 μm
4 cantilevers	D = 0, 250, 500, 1250 μm
5 cantilevers	D = 0, 250, 500, 750, 1250 μm
6 cantilevers	D = 0, 250, 500, 750, 1000, 1250 μm

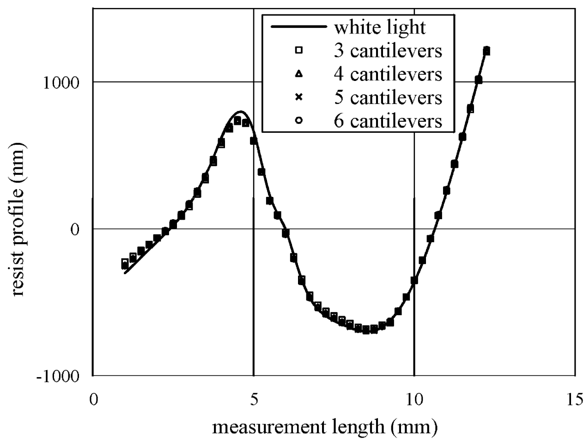

Fig. 9. Calculated results by various numbers of cantilevers with the error separation method. The scanning interval is 250 μm.

in Fig. 8(b), using the least-squares analysis with the error separation method using the autocollimator, we obtain a shape close to the real file. The results demonstrated the feasibility of using this device with the error separation method to calculate the resist profile with high accuracy.

4.3. *Measurement result and discussion of uncertainty*

We made four measurements of the resist thin film using the multi-ball cantilever system. Using the least-squares method, we analyzed the resist profile by 3, 4, 5, and 6 cantilevers. Using the distance of cantilevers D, we used the relation of cantilevers in the calculation listed in Table 1. The analysis results by various cantilever numbers are shown in Fig. 9. Fig. 10 shows the results of four measurements using 6 cantilevers. Figs. 9 and 10 show that the bias in the high-frequency area is bigger than that in the flat area, just like that at the points of 5 and 9 mm. By the correspondence of theoretical analysis with Fig. 11, which shows the experimental standard deviation, we can clearly know that the deviation in the flat area is around 20 nm but that at the edge of the measurement area and the high-frequency area it will be approximately 30–70 nm. This is related to the horizontal resolution of the multi-ball cantilever and scanning interval.

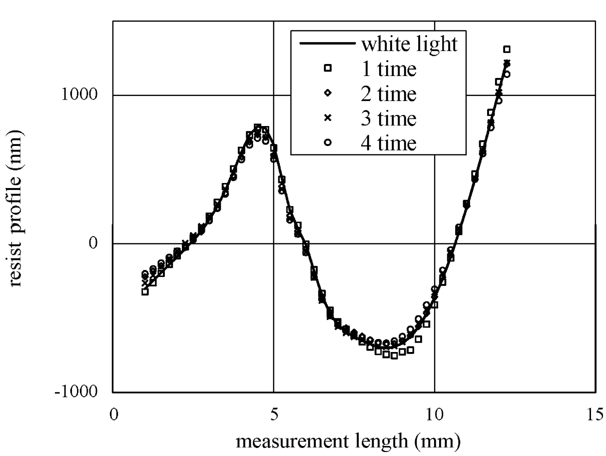

Fig. 10. Calculated resist profile from four measurements by 6 cantilevers. The topography is reconstructed with an average standard deviation of 29.7 nm.

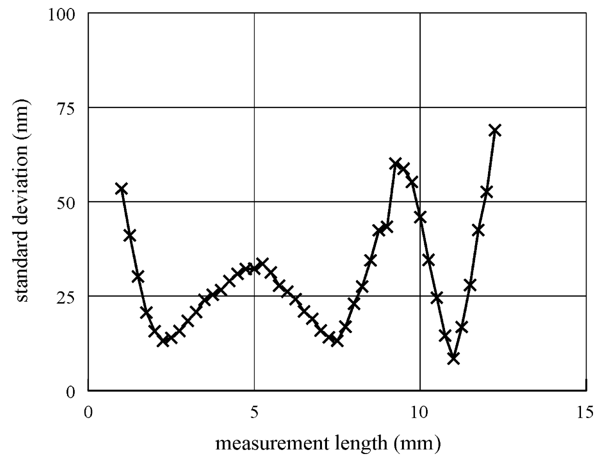

Fig. 11. Experimental standard deviation using 6 cantilevers. The average standard deviation is 29.7 nm.

The uncertainty of the system can be evaluated by the standard deviation using the error propagation method [6]. In the analysis model, the theory uncertainty (Eq. (9)) is assumed to be influenced by the standard deviations of the autocollimator and white light interferometer. Therefore, our estimations give the standard deviations 30 nm and 3 arcsec for the interferometer and autocollimator, respectively [3,7,8]. Table 2 lists the corresponding theory uncertainty and experimental standard deviations for cantilevers of different numbers. Using 3, 4, 5, and 6 cantilevers to calculate the profile gives the theory uncertainty closer to each. The experimental standard deviation from the measurements corresponds with this tendency.

Fig. 12 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 29.7 nm as the average standard deviation. This experimental standard deviation is near to the theory uncertainty when the standard deviation condition on

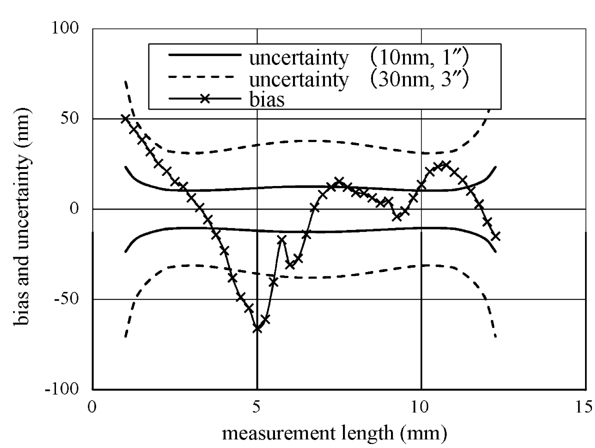

Fig. 12. Example of expanded uncertainty and bias that is the gap between the real profile and the average value of four measurements. The mean uncertainty is 6.4 nm when the standard deviations of the interferometer and autocollimator are assumed to be 10 nm and 1 arcsec, respectively.

Table 2
Standard deviation by four measurements and estimated theory uncertainties

Numbers of cantilevers	Experimental standard deviation (nm)	Theory uncertainty 1 (nm)[a]	Theory uncertainty 2 (nm)[b]
3 cantilevers	41.1	38.44	12.8
4 cantilevers	29.3	23.2	7.7
5 cantilevers	30.2	21.0	7.0
6 cantilevers	29.7	19.1	6.4

[a] Assumed uncertainty of distance sensor and autocollimator = 30 nm, 3 arcsec.
[b] Assumed uncertainty of distance sensor and autocollimator = 10 nm, 1 arcsec.

the interferometer and autocollimator is set to 30 nm and 3 arcsec, respectively. The bias can satisfy a condition of 95% in expanded uncertainty [9]. In the next step, it will be possible to realize a 10-nm order using this system. For example, in the standard deviation condition of 10 nm and 1 arcsec on the interferometer and autocollimator, respectively, the estimated mean uncertainty would be 6.4 nm, as shown in Table 2. We can realize high accuracy by increasing the accuracy of the interferometer and autocollimator.

5. Conclusion

To measure the surface profile of thin film like photoresist, we proposed a method combining light scanning with a mechanical system involving a multi-ball cantilever. According to the scanning stage and systematic sensor errors, the error separation method together with an autocollimator was discussed with regard to the feasibility of the multi-ball cantilever.

The results of this study are summarized as follows:

(1) Using the white light interferometer, multi-ball cantilever, and autocollimator, we constructed a measurement mechanism, a multi-ball cantilever system.
(2) The surface measurements of resist thin film were carried out using the multi-ball cantilever system. Compared to the normal 3-point method without an autocollimator, the error separation method with an autocollimator verified the validity of this system. Moreover, we showed that this system has the possibility of high-speed measurement.
(3) From four scanning experiments, the topography was reconstructed with a standard deviation of 29.7 nm by 6 cantilevers. Corresponding to a discussion of the theory uncertainty, the system can be expected to measure photoresist thin film with a 10-nm resolution.

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