IN-SITU SELF-CALIBRATION OF TWO-DIMENSIONAL ANGLE PROBE FOR PROFILE MEASUREMENT OF LARGE SILICON WAFERS

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1. Introduction

Flatness metrology of silicon wafer substrates is an essential process for semiconductor manufacturing [1]. The undergoing transition from 200 mm diameter wafers to 300 mm diameter wafers has being brought about a great challenge to the flatness measuring technology. Comparing with interferometer-based systems, the scanning probe systems are much easier to be advanced to measure large wafers through expanding the travel of the scanning stage.

The authors are developing a scanning angle probe system for flatness metrology of large silicon wafers [2-4]. The proposed system employs two two-dimensional (2D) angle probes, which detect the 2D local slopes (X- and Y-directional local slopes) at two points on the wafer surface. In this angle-based measuring system, the translational error motions of the probe carriage (straightness error motions) and the wafer spindle (axial error motion) will not appear in the probe outputs. Based on the concept of error separation [5], the 2D local slopes of the wafer surface can be separated from the angular error motions of the probe carriage (pitch, roll) and the wafer spindle (angular error motion) using the 2D outputs of the angle probes [4]. The cross-sectional height profiles of the wafer surface along radial directions can be obtained through integrating the X-directional local slopes of the wafer surface, and the cross-sectional height profiles along concentric circles can be obtained through integrating the Y-directional local slopes. The height profile of the entire wafer surface can thus be evaluated from combining the sectional profiles in these two directions.

To realize the 2D angle-based scanning probe method with nanometer accuracy, highly sensitive and accurate 2D angle probes are necessary. The authors have successfully developed a compact and sensitive 2D angle probe [2,4]. In this paper, we apply an in-situ self-calibration method [6] to the calibration of the 2D angle probe when the angle probe and the wafer are mounted in the scanning system.

2. Principle of the in-situ self-calibration

Figure 1 shows the 2D angle-based scanning probe system. For the sake of clarity, only one of the two angle probes is shown in the figure. The angle probe is mounted on a linear X-carriage, and the wafer is mounted on a wafer spindle.

Assume that the X- and Y-directional calibration curves of the 2D angle probe are described by functions $A_X(v_X)$ and $A_Y(v_Y)$, in which v_X and v_Y are outputs of the angle probe. Figure 2 shows an example of the calibration curves. In Fig. 2, the vertical axis represents the detected angle τ_X (the angle around Y-axis) (or τ_Y: the angle around X-axis), and the horizontal axis represents the corresponding probe output v_X (or v_Y). When use an angle probe, it is necessary to evaluate the detected angle τ_X (or τ_Y) from the probe output v_X (or v_Y) based on the function $A_X(v_X)$ (or $A_Y(v_Y)$). To obtain the function $A_X(v_X)$ ($A_Y(v_Y)$) is the objective of the calibration.

Here, we propose an in-situ self-calibration method that can realize the calibration in the wafer measuring system shown in Fig.1, where the angle probe is moved by the X-carriage to scan the wafer surface while the wafer is being rotated by the spindle. Differing from a conventional calibration process, in which the angle τ_X (or τ_Y) in Fig. 2 needs to be measured by

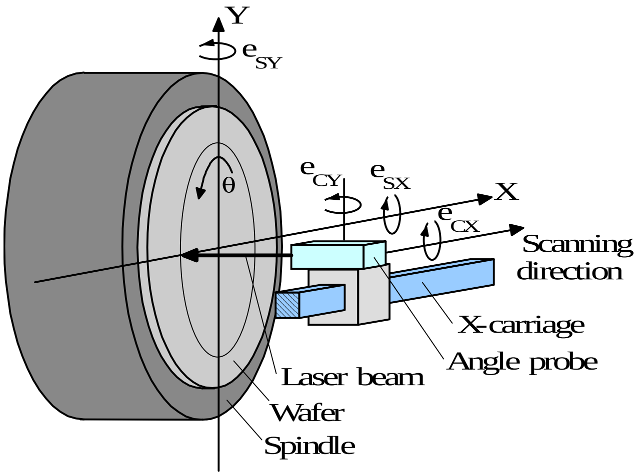


Figure 1 The scanning angle probe system

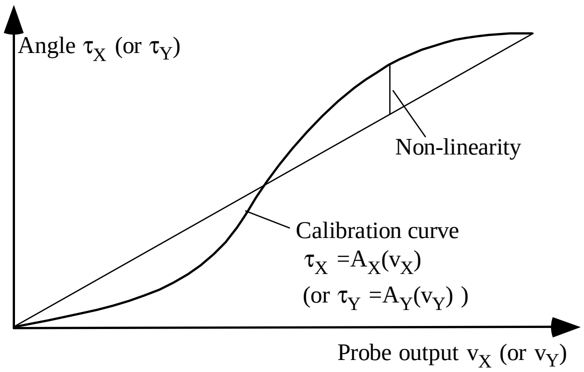


Figure 2 An example of the calibration curve

an accurate reference angle sensor, the proposed calibration technique utilizes the profile measurement data of a wafer surface.

Assume that the scanning in X-direction starts from the center of the wafer and the sampling positions are numbered as x_i (i=1, 2, ..., M) as shown in Fig. 3. At each position x_i, the 2D angle slopes of the wafer surface at points along a circle are sampled by the angle probe. If the sampling positions along the circle are numbered as θ_j (j=1, 2, ..., N), the following equations can be obtained.

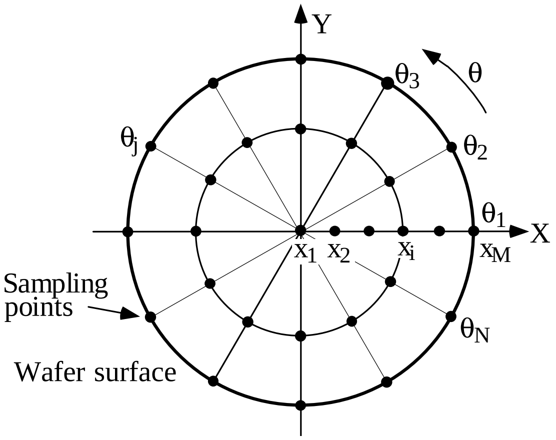


Figure 3 Sampling positions on the wafer surface

$$A_X(v_X(x_i,\theta_j)) = f'_X(x_i,\theta_j) + e_{CY}(x_i) + e_{SY}(x_i,\theta_j) \qquad (1)$$

$$A_Y(v_Y(x_i,\theta_j)) = f'_Y(x_i,\theta_j) + e_{CX}(x_i) + e_{SX}(x_i,\theta_j) \quad \text{i=1,2,…, M, j=1,2, … N} \qquad (2)$$

where $v_X(x_i,\theta_j)$ and $v_Y(x_i,\theta_j)$ are the X- and Y-directional outputs of the angle probe at sampling position (x_i,θ_j), respectively. $A_X(v_X(x_i,\theta_j))$ and $A_Y(v_Y(x_i,\theta_j))$ are the corresponding X- and Y-directional angles detected by the angle probe. $e_{CX}(x_i)$ and $e_{CY}(x_i)$ are the roll error and yaw error of the X-carriage, respectively. $e_{SX}(x_i,\theta_j)$ and $e_{SY}(x_i,\theta_j)$ are the angular motion components of the wafer spindle around X- and Y-axes. $f'_X(x,\theta)$ and $f'_Y(x,\theta)$ are the X- and Y-directional local slopes of the wafer surface, which are defined as:

$$f'_X(x,\theta) = \partial f(x,\theta)/\partial x, \quad f'_Y(x,\theta) = \partial f(x,\theta)/\partial y \qquad (3)$$

After the first scanning, we tilt the wafer or the probe by a small angle $\Delta\phi$ around the Y-axis, and then perform the second scanning to get the following equations.

$$A_X(v_{X+}(x_i,\theta_j)) = f'_X(x_i,\theta_j) + e_{CY}(x_i) + e_{SY}(x_i,\theta_j) + \Delta\phi\cos\theta_j \qquad (4)$$

$$A_Y(v_{Y+}(x_i,\theta_j)) = f'_Y(x_i,\theta_j) + e_{CX}(x_i) + e_{SX}(x_i,\theta_j) + \Delta\phi\sin\theta_j \qquad (5)$$

i=1,2,…, M, j=1,2, … N

where $v_{X+}(x_i,\theta_j)$ and $v_{Y+}(x_i,\theta_j)$ are the X- and Y-directional outputs of the angle probe at sampling position (x_i,θ_j) in the second scanning, respectively. $A_X(v_{X+}(x_i,\theta_j))$ and $A_Y(v_{Y+}(x_i,\theta_j))$ are the corresponding X- and Y-directional angles detected by the angle probe.

The data shown in Eqs. (1) and (4) are used to evaluate the calibration function $A_X(v_X)$ of the X-directional output of the angle probe. Taking the difference of Eqs. (4) and (1) gives :

$$A_X(v_{X+}(x_i,\theta_j)) - A_X(v_X(x_i,\theta_j)) = \Delta\phi\cos\theta_j \tag{6}$$

where the terms of surface slopes and motion errors are removed.

In most cases, for a fixed θ_j, the raw data of the voltage output $v_X(x_i,\theta_j)$ and $v_{X+}(x_i,\theta_j)$ with respect to the sampling position x_i will have a relationship shown in Fig. 4(a), which do not progressively increase or decrease with respect to x_i. As shown in Fig. 4(b), before conducting the calculation of the calibration function, we rearrange the data as $v_X(m,\theta_j)$ and $v_{X+}(m,\theta_j)$ (m=0, 1, ..., M) so that the data progressively increase or decrease with respect to the new X-data number m (the case of increase is taken as an example in the figure).

For a fixed θ_j (θ_j is not equal to 90 and 270 degrees), an approximate derivative of $A_X(v_X(m))$ can be obtained from:

$$A'_X(v_X(m)) \approx \frac{A_X(v_{X+}(m,\theta_j)) - A_X(v_X(m,\theta_j))}{v_{X+}(m,\theta_j) - v_X(m,\theta_j)} = \frac{\Delta\phi\cos\theta_j}{v_{X+}(m,\theta_j) - v_X(m,\theta_j)} \tag{7}$$

$$m=1,2,\ldots,M$$

As shown in Fig. 4(c), the calibration function of the X-directional output $A_X(v_X)$ can thus be obtained through integration of $A'_X(v_X)$ with respect to $v_X(m)$ as:

$$A_X(v_X(m)) = \sum_{w=1}^{m} A'_X(v_X(w))(v_X(w+1,\theta_j) - v_X(w,\theta_j)) \qquad m=1,2,\ldots,M-1 \tag{8}$$

On the other hand, the calibration function of the Y-directional output $A_Y(v_Y)$ can be obtained through using the data of Eqs. (2) and (5), in which x_i is fixed:

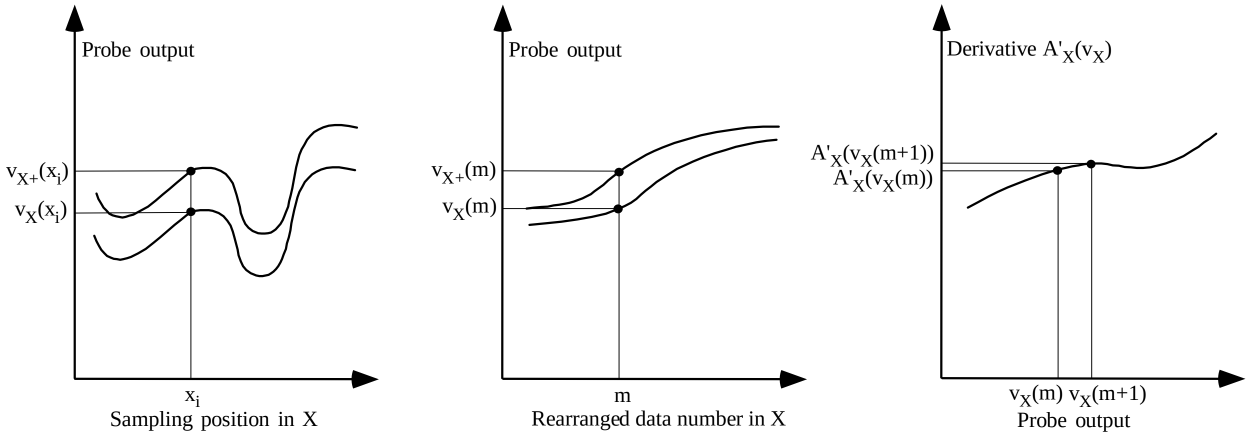
$$A_Y(v_Y(n)) = \sum_{u=1}^{n} A'_Y(v_Y(u))(v_Y(x_i,u+1) - v_Y(x_i,u)) \quad n=1,2,\ldots,N-1 \tag{9}$$

where the probe output data are rearranged to progressively increase or decrease with respect to the new θ-data number n, and

$$A'_Y(v_Y(n)) \approx \frac{A_Y(v_{Y+}(x_i,n)) - A_Y(v_Y(x_i,n))}{v_{Y+}(x_i,n) - v_Y(x_i,n)} = \frac{\Delta\phi\sin\theta_n}{v_{Y+}(x_i,n) - v_Y(x_i,n)}$$

$$n=1,2,\ldots,N \tag{10}$$

As can be seen from above, the calibration result in each sensitive direction of the angle probe can be obtained from two sets of angle probe outputs of sampling the wafer surface before and after a small tilt of the wafer (or the angle probe) without the influence of the wafer surface slopes and the error motions of the X-carriage and the spindle.



(a) Raw data of sampling (b) Rearranged data (c) Derivative of the calibration function

Figure 4 Data processing procedure of calibrating the X-directional output of the angle probe

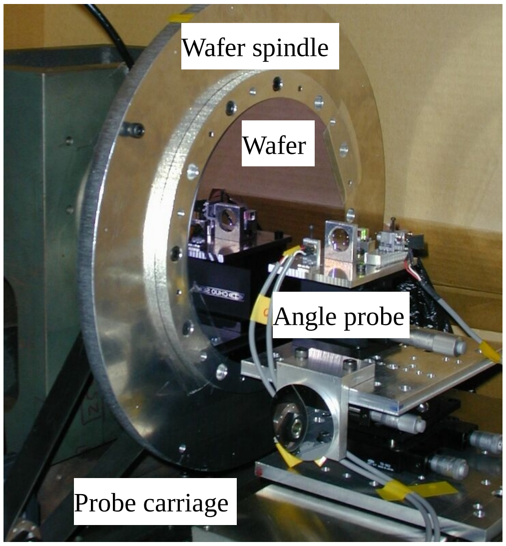


Figure 5 Experimental system

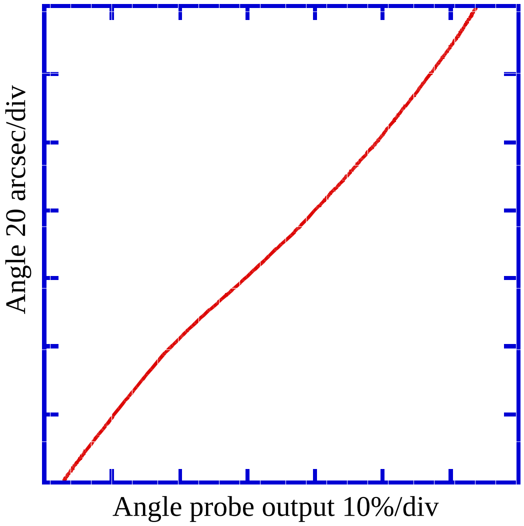


Figure 6 An X-directional calibration result

3. Experiments

Figure 5 shows a photograph of the experimental system. The wafer was mounted vertically on an air-spindle. A stepping motor-driven stage was used as the X-carriage. A 200 mm diameter wafer was used as the specimen. In the experiments, the tilt $\Delta\phi$, which is necessary for the calibration, was applied to the angle probe. The tilt was measured by a Nikon autocollimator.

Figure 6 shows one of the in-situ self-calibration results. The result of the X-directional output was shown in the figure. The vertical axis shows the detected angle in arc-second, and the horizontal axis shows the probe output in percentage. The non-linearity was approximately 10 arc-seconds in a calibration range of 140 arc-seconds.

4. Conclusions

An in-situ self-calibration technique has been proposed to calibrate a 2D angle probe developed for flatness metrology of large silicon wafers. The two-dimensional outputs of the angle probe can be calibrated from two repeated sampling of the wafer surface before and after a small tilt of wafer or the angle probe. The only condition for the calibration is the repeatability of the scanning motion, and this is not an issue for the air-bearing based probe carriage and wafer spindle.

Acknowledgements

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