The Evaluation and Research of white light interference profiler about the measurement uncertainty

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Abstract. The optical resolution of the white light interferometer characterized by higher sensitively and accurately with 580nm wavelength approximately is 5nm. However, as a new non-contact measurement equipment, the white light interferometer has certain measurement errors. In this paper, we propose a novel method that the accuracy of the white light interference profiler is evaluated by measuring the nano grating standard structure. The standard step height and pitch sample were used in the measurement process, and the morphological characteristics of the sample were obtained by Fourier transform, phase modulation and phase splicing of the sampled data. The experimental results show that the horizontal and vertical extension uncertainty of the white light interference profiler is 174nm and 8.07nm, respectively.

1. Introduction

As the basis of the information industry, the nanometer semiconductor components have penetrated into all areas of life. And these have not only became the important symbol of national comprehensive strength and international competitiveness at the information age, but also been the fundamental guarantee of national security and national defense construction. Thus, making the measurement of nanometer semiconductor components in the micro-nano structure is particularly critical [1]. According to the International authoritative semiconductor industry trends shows that if the chip components exist one tenth of the error, it will be failure in the performance. At present, the characterization methods about the micro-nano structure of elements mainly include the optical detection and non-optical detection. And the non-optical detection mainly includes mechanical probe method [2], the atomic force microscope (AFM) [3], scanning tunneling microscope (STM) and scanning electron microscope (SEM). The optical detection mainly includes the confocal laser scanning microscope [4], digital holography [5], structured light projection microscopy and white light interferometry.

The purpose of this paper is to study the measurement uncertainty of white light interference profiler, which has the characteristic of large measurement range, high resolution and the non-contact detection [6-7]. The white light interferometry as a novel measurement method is illustrated by
introducing the nanometer measurement. For evaluating uncertainty of measurement results and gaining the sources of the uncertainty of white light interference profiler, we mainly introduce principle and basic structure of white light interference profiler.

2. Traceability of nano-metrology
Nanometer geometric measurement instruments can directly or indirectly measure the nanoscale geometric devices, instruments or measuring tools, including gage reference, gage standard and working gage [8-9]. As described below, the nanometer reference meter is a measuring instrument that replicates the nanometer geometric quantity value, the highest accuracy level and served as the highest basis for unifying the national nanometer geometric quantity value [10]. All levels of the nanometer standards and the working measuring instruments must be directly or indirectly traceable to nanometer reference meters, mainly including five devices: millimeter scale nanometer geometric structure sample calibration device, nanometer geometric structure standard device, nanometer sample calibration device, ultraviolet light two-dimensional nanometer geometric structure standard device, and double probe nanometer line width calibration device. The metering standards are mainly samples, which are particles and films with a certain step height, grid spacing or line width [11]. For industrial production, processing and manufacturing, the working measuring instrument is used to evaluate the quality of nanometer geometry and surface morphology. Including scanning probe microscope, electron microscope, optical microscope, particle size shape measuring instrument, and film thickness measuring instrument, etc. [12].

The specific trace system of micro-nano is shown as figure 1:

![Figure 1. Traceability of nano-metrology.](image)

3. Theory
According to the distribution theory of light intensity, the intensity of the white light interference profiler can be expressed as:

\[
I(x,y) = A_{2n}(x,y) + B_{2n}(x,y) \cos\left(\frac{4\pi}{\lambda_0}(z_0 - h(x,y) - kx)\right)
\]

(1)

where

\[
B_{2n}(x,y) = A_{2n}(x,y) \exp\left[\frac{\left(\frac{z_0 - h(x,y) - kx - z_0}{\lambda_0}\right)}{i\epsilon}\right]
\]

(2)

(x, y) is the transverse coordinate of the sampling point, \(A_{2n}(x,y)\) represents the interference background light intensity of \(z_0\) at the scanning position, \(B_{2n}(x,y)\) is the contrast of the image, \(z_0\) is the length of the reference arm, \(h(x,y)\) is the height information of the measured structure, and \(k\) is the
tilt factor of the measured object, $I_x$ is the coherence length of the broad spectrum light source, and $\lambda_0$ is the central wavelength of the light source. The transformation of equation (1) can be obtained.

$$I(x, y) = A_2n(x, y) + B_2n(x, y) \cos(2\pi f_1 + \Phi(x, y)) \tag{3}$$

According to Euler's transformation rule, equation (3) can be expressed as:

$$I(x, y) = A(x, y) + C(x, y) e^{i2\pi f_1} + C(x, y) e^{-i2\pi f_1} \tag{4}$$

In which $C(x, y) = \frac{1}{2} B(x, y) e^{-i\Phi(x, y)/\lambda_0}$, express the initial phase difference. $f = \frac{k}{\lambda_0}$ is the wave speed.

$$\Phi(x, y) = 4\pi \frac{z_n - h(x, y) - z_0}{\lambda_0}$$ represents the initial phase, and in the complex frequency domain can be expressed as: $\Phi(x, y) = \text{Angle}[C(x, y)]$

The phase of the interference image is analyzed by Fourier transform method. The single frame interference image is analyzed independently, and intensity of the spatial light is converted into frequency domain information. The fundamental frequency information is extracted, and the inverse Fourier transform is performed to extract the interference phase information in the complex frequency domain. Figure 2 shows the process of the Fourier transform algorithm. The two ends of equation (4) were transformed by two-dimensional Fourier transform, and the spectrum analysis was as follows:

$$G(f_x, f_y) = G_M(f_x, f_y) + D_1(f_x, f_y) \otimes G_1(f_x, f_y) + D_1(f_x, f_y) \otimes G_1(f_x, f_y) \tag{5}$$

$$D_1(f_x, f_y) = F[C(x, y)] \tag{6}$$

The fundamental frequency signal $D_1(f_x, f_y)$ is extracted through the filter window, and then $C(x, y)$ can be obtained by the inverse Fourier transform.

The interference phase is extracted by Fourier transform, and the longitudinal scan error is not affected due to each image is analyzed independently.

![Figure 2. The process of Fourier transform analysis.](image)

The phase distribution is extracted by Fourier transform algorithm and the modulation distribution is calculated. According to the modulation threshold and the "01" phase unwrapping template, the pixels are judged to be valid points. If the pixel point modulation system is higher than the set threshold, the corresponding phase unwrapping template is "1". The diamond phase unwrapping algorithm is used to calculate the continuous phase of the point. When the pixel point modulation is lower than the set threshold, the corresponding point phase unwrapping template is "0", and no phase unwrapping operation is performed. For the interference image of two adjacent frames, a part of pixel points can be adjusted well at two different scanning positions. Continuous phase unrolling of effective pixel points is used, and then longitudinal phase splicing performed on the pixels is to obtain the continuous phase distribution of the whole field in both frames.
4. **White light interference profiler**

The white light interference profiler is mainly used to measure the surface morphology of nanometer integrated device. This device is mainly composed of interferometry system, phase shifting system, CCD and analysis software, as shown in figure 3. After the collimation of the expanded beam, the incident light is divided into two beams by the beam splitting prism. One incident beam forms reflected light on the surface of the sample to be measured, and the other incident beam forms reflected light on the surface of the reference mirror. The two reflected beams occur interfere on the contrary surface of the beam splitting prism. When the distance from the spectroscope to a point on the measured surface is equal to the distance from the spectroscope to the reference mirror, the optical path difference of the corresponding two beams of interference light is zero, and then the interference light intensity is the largest. Due to the roughness on the surface of the measured object, the resulting interference light intensity is different. Therefore, the interference fringe signals with the surface morphology characteristics of the measured object can be obtained by moving the measured object or the reference mirror. Then the three-dimensional surface morphology can be measured by measuring the changes of the interference fringes.

![Schematic diagram of white light interference](image)

Figure 3. Schematic diagram of white light interference.

In this study, the white light interference profiler is independently developed by the Institute of Photoelectric Technology, Chinese Academy of Sciences. As shown in figure 4, it is illuminated by a 580nm wavelength light source with a field of 50 microns view, a magnification rate is 10 times and a resolution is 0.1nm. The resolution of the microscope ensures the ability to measure the microchip size and the line width and step size of the mask.
5. **Calibration Method**

5.1. **Vertical (Z) step measurement method**

The effective measurement area of the sample was at the left, middle and right positions respectively. The structure composed of ABC as shown in figure 5, was selected at each position. The pitch was the middle 1/3 period of calculation. The measurements were repeated 10 times at each location, then calculated an average value. The measured value $h_i$ of step height is expressed by the following equation (7) and equation (8)(unit nm):

$$h_i = \frac{\sum_{j=1}^{m} B_j}{m} = \frac{\sum_{j=1}^{n} A_j + \sum_{j=1}^{n} C_j}{2n}$$

$$h = \frac{\sum_{i=1}^{d} h_i}{d}$$

Where: $h_i$--the height of one step;

$A_i, B_i, C_i$ represent measurement value of z-axis in the region A, B and C, respectively;

$m$--Number of points measured in the region B;

$n$--Number of measuring points in the region A and C;

$h$--Means of measured height of step;

$d$--Number of repeated measurements.

5.2. **Horizontal (X, Y) interval measurement method**

For measuring the uncertainty of the white light interference profiler, the three regions (0% ~ 30%,
40% ~ 60% and 70% ~ 100%) in the horizontal direction must be measuring at least once. Meanwhile, the fitted curve should contain more than 6 lines pitch in each region. The measurement data, which is more than 50% at the height of each scribed line, is used to calculate the centroid coordinate by centroid method. The calculation equation of the specific centroid coordinate is as follows:

\[ l_n = \frac{\sum_{i=1}^{s} X_i Z_i}{\sum_{i=1}^{s} Z_i} \]  

where \( l_n \) — is the centroid coordinate of the \( n^{th} \) line center along the measurement direction in the selected region;

\( Z_i \) — Z coordinate of measurement point;

\( X_i \) — the X coordinate of measurement point;

\( s \) — Number of measurement points.

The centroid coordinates of the first and last scribed lines were calculated respectively, and the results of a single periodic measurement can be calculated by equation (10). Using this method to repeat the measurement of each point at 10 times, and the average value of these measurements was taken as the line interval according to equation (11).

\[ F_i = \frac{l_n - l_1}{n-1} \]  

\[ F = \frac{\sum_{i=1}^{m} F_i}{m} \]

where \( n \) is the number of line pitch, equal or greater than 6;

\( P_i \) represent the single result of line interval;

\( F \) represent the Means value of line pitch.

The centroid coordinate of horizontal interval measurement is shown in figure 6:

![Figure 6. The centroid coordinate measured at horizontal intervals.](image)

6. Evaluation and analysis of measurement uncertainty

The period of the standard nanometer grating sample used in this experiment is 4.830 μm, and the measurement uncertainty of period is \( U=0.004 \mu m \) (k=2). The calibration value of step height is 99.8nm, and the measurement uncertainty of step height is \( U=1.5 \text{ nm} \) (k=2). The millimeter level of nanometer geometry model developed by the National Institute of Metrology (NIM, China) is as the standard device for calibrating the nano-grating model, which can be used to measure the range of 10mm×10mm×5μm. The measurement uncertainty of z axis is \( U=1.0 \text{ nm} +10^{-5} H \) (k=2), \( H \) is the displacement on the z axis. The measurement uncertainty of transverse axis is \( U=1.0 \text{ nm} +2 \times 10^{-7} P \) (k=2), \( P \) is the displacement.

The indication errors of white light interference profiler include the vertical direction indicating errors and the horizontal direction indicating errors. Different white light interferometer profilers have different measuring ranges, and the standard templates of different step height and span are selected in the actual measurement process. The measurement uncertainty is evaluated and analyzed by the white light interferometer.
6.1. Assessment of measurement uncertainty

The measurement uncertainty of the two directions mainly are introduced by the superior standard, the measurement repeatability, the measurement resolution, and temperature change.

6.1.1. Measurement mode

The measurement model is defined as shown in equation (12). The vertical direction indication errors of the white light interference profiler is:

\[ h = H - H_0 \]  

Where: \( H \) is measured value of step height, the unit of which is nm; \( H_0 \) is the Nominal step height in nm.

The measurement model is expressed as equation (13). The horizontal direction indication errors of the white light interference profiler is:

\[ f = F - F_0 \]  

Where \( F \) is the measured value in the horizontal direction of the white light interference profiler; \( F_0 \) is the nominal value of the pitch standard template.

6.1.2. Measurement uncertainty \( u_{H1} \) and \( u_{F1} \) is introduced by step height and span of standard template span is expressed below

\[ u_{H1} = \frac{6 + 2 \times 10^{-5} H_0}{2} \]  

\[ u_{F1} = \frac{4 + 1 \times 10^{-4} F_0}{2} \]

6.1.3. Measurement uncertainty is introduced by the repeatability measurement:

The same measurement position of the sample was repeated for 10 times, and Bessel function was used to calculate the standard deviation of \( s_H \) and \( s_F \) respectively. Then the measurement uncertainty introduced by the repeatability measurement was:

\[ u_{H2} = s \]  

\[ u_{F2} = s \]

6.1.4. Measurement uncertainty is introduced by the measurement resolution:

The measurement resolution is 0.1 nm in the vertical direction and 0.3 mm in the horizontal direction, respectively. According to the uniform distribution, the measurement uncertainty introduced by the resolution is:

\[ u_{H3} = \frac{0.1}{2\sqrt{3}} \approx 0.029 \text{ nm} \]  

\[ u_{F3} = \frac{300}{2\sqrt{3}} \approx 86.6 \text{ nm} \]

6.1.5. Measurement uncertainty is introduced by change of measurement sample size due to temperature change

When the temperature variation, which caused by the variation of environmental temperature and light irradiation temperature, will cause the change of size of geometry model. The expansion coefficient of silicon material is \( \alpha = 2.5 \times 10^{-6} \text{ C}^{-1} \), and the range of temperature variation is generally controlled
at \( \pm 1 \, ^\circ\text{C} \) in the measurement process. According to the uniform distribution, the uncertainty components can be estimated by

\[
u_{H4} = \frac{2.5 \times 10^{-6} \times 1}{\sqrt{3}} H_0
\]

\[
u_{F4} = \frac{2.5 \times 10^{-6} \times 1}{\sqrt{3}} F_0
\]

6.1.6. Uncertainty of synthetic standard

\[
u_{He} = \sqrt{u_{H1}^2 + u_{H2}^2 + u_{H3}^2 + u_{H4}^2}
\]

\[
u_{Fc} = \sqrt{u_{F1}^2 + u_{F2}^2 + u_{F3}^2 + u_{F4}^2}
\]

6.1.7. Extended measurement uncertainty

\[U_{He} = k \times \nu_{He}\]

\[U_{Fc} = k \times \nu_{Fc}\]

The uncertainty measured in the vertical direction is shown in Table 1, and the uncertainty measured in the horizontal direction is shown in Table 2.

| Source of Measurement uncertainty | coverage factor \( k \) | Measurement uncertainty value(nm) |
|-----------------------------------|-------------------------|----------------------------------|
| The uncertainty component introduced by the superior standard \( u_{H1} \) | 2 | 3.001 |
| The uncertain component introduced by repeatability \( u_{H2} \) | 1 | 2.699 |
| The uncertainty component introduced by vertical resolution \( u_{H3} \) | \( \sqrt{3} \) | 0.029 |
| The uncertainty component caused by temperature change \( u_{H4} \) | \( \sqrt{3} \) | 0.001 |
| Synthetic measurement uncertainty \( u_{He} \) | 2 | 4.036 |
| Extended measurement uncertainty \( U_{He} \) | 2 | 8.073 |

| Source of Measurement uncertainty | coverage factor \( k \) | Measurement uncertainty value(nm) |
|-----------------------------------|-------------------------|----------------------------------|
| The uncertainty component introduced by the superior standard \( u_{F1} \) | 2 | 2.2 |
| The uncertain component introduced by repeatability \( u_{F2} \) | 1 | 0.0 |
| The uncertainty component introduced by horizontal resolution \( u_{F3} \) | \( \sqrt{3} \) | 86.6 |
| The uncertainty component caused by temperature change \( u_{F4} \) | \( \sqrt{3} \) | 0.0 |
| Synthetic measurement uncertainty \( u_{Fc} \) | 2 | 86.6 |
6.2. Measurement data and analysis

In the whole process of scanning, as there are several million points in the result of scanning measurement, a portion of the data is intercepted as shown in figure 7. In the coordinate system, the X-axis and Y-axis directions are pixel points, and the Z-axis direction is the vertical height, the unit of which is nm. Both horizontal and vertical measurements are measured over and over, the image of part of measurement data is shown in figure 8. In this coordinate system, the X-axis is pixel points and Y-axis is span about the height of measurement sample. From the aspect of measurement uncertainty analysis, the measurement uncertainty of the vertical direction is introduced by the superior standard and the measurement repeatability. Meanwhile, the horizontal resolution lead to the horizontal measurement uncertainty. From the results of measurement accuracy, the horizontal measurement results are more accurate, but the vertical measurement is relatively difficult and more easily inaccurate.

| Extended measurement uncertainty $U_p$ | 2   | 173.3 |

Figure 7. Schematic diagram of scanning results.

Figure 8. Schematic diagram for measurement.
7. Conclusion
The 580nm wavelength microscope greatly improves the resolution of the white interference profiler and images lines with micro-nano width and span. We study that the measurement uncertainty of the white light interference profiler, which has an important reference value for analyzing and evaluating the indication error of the equipment, to obtain the final extended uncertainty. Further improvement of horizontal resolution and vertical repeatability for measurement results can improve the performance of the equipment.

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