The Evaluation and Research of step profiler about the measurement uncertainty

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Abstract. The step profiler has the advantages of excellent repeatability and high resolution. However, as a new contact measurement equipment, it has specific measurement errors. This paper proposes a novel method to evaluate a step profiler’s accuracy by measuring the nano grating standard structure. These standard step height and pitch samples are used in the measurement process. The samples’ morphological characteristics were obtained by Fourier transformation, phase modulation, and phase splicing of the sampled data. The experimental results show that the step profiler’s vertical and horizontal relative measurement uncertainty is 4.0% and 1.2%.

1. Introduction
The nanometer semiconductor components have penetrated all areas of life. And these have not only become the vital symbol of comprehensive national strength and international competitiveness at the information age but also the fundamental guarantee of national security and national defense construction. Thus, measuring nanometer semiconductor components in the micro-nano structure is particularly critical [1]. At present, the characterization methods about the micro-nano structure of elements mainly include optical detection and non-optical detection. And the non-optical discovery mainly consists of the 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 scanning microscope [4], digital holography [5], structured light projection microscopy, and white light interferometry.

This paper aims to study the measurement uncertainty of step profiler, which has the characteristic of large measurement range, high resolution, and contact detection [6]. The Mechanical probe method as an efficient measurement method is illustrated by introducing the nanometer measurement. To evaluate the uncertainty of measurement results and gain the sources of the uncertainty of step profiler, we mainly introduce principles and the basic structure of step profiler.

2. Traceability of nano-metrology
Nanometer geometric measurement instruments, including gage reference, gage standard, and working gage [7-8]. The gage reference 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 dual probe nanometer line width calibration device. The metering standards are mainly samples, particles, and films with a confident step height, grid spacing, or line width [9]. The working gage
includes scanning probe microscope, electron microscope, optical microscope, particle size shape measuring device, and film thickness measuring device, etc. [10].

3. Principle of measurement
The step measuring instrument is mainly used to measure the surface morphology of the nano-integrated device structure. According to the different sensors, the level measuring instrument can be divided into inductance type, a piezoelectric type, and photoelectric type. It is mainly composed of displacement sensors, processing circuits, A/D converter, contour analysis software, etc., as shown in Figure 1. A diamond contact needle with a radius of several microns is used to scan along the measured surface. The contact needle’s vertical displacement is converted into a corresponding electrical signal output by the displacement sensor. After A/D conversion by the processing circuit, the contact needle is sent to the computer to obtain the step’s surface outline and parameters [11].

![Figure 1. Schematic diagram of step height measuring.](image)

For the step measuring instrument, the accuracy of roughness directly determines the accuracy of step measuring. In the past, the contour line is the theoretical basis for quantitatively describing and evaluating the surface. It is an imaginary reference line for obtaining the surface roughness value, which occupies a place in instrument theory. The international standard recommends using a Gaussian filter to establish the reference line of surface evaluation. The weight function of the filter is:

\[ H(t) = \frac{1}{k\lambda_0} e^{-\pi m} \]  
\[ m = \frac{t^2}{(k\lambda_0)^2} \]  

Here \( \lambda_0 \) is the excised wavelength, \( k \) is a constant, and the attenuation at the specified excised wavelength is determined. When the specified transmission value is 50%, the Gaussian distribution function with zero mean is:

\[ \Phi(t) = \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}} \]

\[ \lambda_0 = \pi \sigma \sqrt{\frac{2}{\ln 2}} = 5.34\sigma \]

The Fourier transform of the Gaussian is still a Gaussian. The amplitude transfer characteristic or frequency response of the Gaussian filter can be obtained by applying the Fourier transform of \( H(t) \):

\[ H(w) = |H(w)| = | \frac{1}{2\pi} \int_{-\infty}^{\infty} h(t) e^{-j\omega t} dt | = e^{-\frac{\pi (\omega \lambda_0)^2}{( \lambda \sigma )^2}} \]

Where \( \alpha = \sqrt{\frac{\ln 2}{\pi}} \) is a constant.

Gauss filter is essentially a low pass filter with a transmission rate of 50% at the cut length, which can realize undistorted phase transmission.

In this study, the equipment used was the Brock step profiler in Germany, as shown in Figure 2. The scanning length range was 55mm, the vertical measurement range was 1mm, and the vertical resolution was 0.1nm. The decision ensures the ability to measure the microchip size and the line width and step size of the mask.
4. Calibration Method

4.1. Vertical step measurement method

The sample’s active measurement area was at the left, middle, and right positions, respectively[12]. The structure composed of ABC, as shown in figure 3, was selected at each position. The pitch was the middle 1/3 period of calculation. The measurements were repeated ten times at each location, then calculated the average value. The measured value $h_o$ of step height is expressed by the following equation (7) and equation (8)(unit nm):

$$h_o = \frac{\sum_{i=1}^{m} B_i - \sum_{i=1}^{n} A_i + \sum_{i=1}^{n} C_i}{m}$$

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

Where:
- $h_o$--the height of one step;
- $A_i, B_i, C_i$ represents the 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 the measured height of step;
- $d$--Number of repeated measurements.

4.2. Horizontal interval measurement method

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

$$l_n = \frac{\sum_{i=1}^{z} X_i Z_i}{\sum_{i=1}^{z} Z_i}$$

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 each point’s measurement at ten times, the average value of these measurements was taken as the line interval (11).

\[
F_i = \frac{n_i - l_i}{n_i - l_i}
\]

\[
F = \frac{\sum F_i}{m}
\]

where $n$ is the number of line pitch, equal to or greater than six;

$P_i$ represents the single result of line interval;

$F$ represents the Means value of line pitch.

5. 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 the 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 $U=1.5nm$ ($k=2$). The millimeter level of the nanometer geometry model developed by the National Institute of Metrology (NIM, China) is the standard device for calibrating the nano-grating model, measuring the range of 10mm×10mm×5 μm. The measurement uncertainty of the z-axis is $U=1.0nm+\frac{1}{10}H$ ($k=2$), $H$ is the displacement on the z-axis.

The measurement uncertainty of the transverse axis is $U=1.0nm+2 \times 10^{-7}P$ ($k=2$), $P$ is the displacement.

The indication errors of step profiler include the vertical direction reporting errors and the horizontal direction indicating errors. The measurement uncertainty is evaluated and analyzed by step profiler.

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

Measurement model. The measurement model is defined as shown in equation (11). The vertical direction indication errors of step profiler are: $h=H-H_0$ (11)

Where: $H$ is the 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 (12). The horizontal direction indication errors of step profiler are: $f=F-F_0$ (12)

Where $F$ is the measured value in the horizontal direction of step profiler;

$F_0$ is the nominal value of the standard pitch template.

Measurement uncertainty $u_{H1}$ and $u_{F1}$ is introduced by step height, and span of standard template span is expressed below.

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

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

The same measurement position of the sample was repeated ten times, and the 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:

\[
u_{H2} = S
\]

\[
u_{F2} = S
\]

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

\[
u_{H3} = \frac{0.1}{2\sqrt{3}} = 0.029 \text{ nm}
\]
\[ u_{F3} = \frac{100}{2\sqrt{3}} \approx 29.8 \text{ nm} \] (18)

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

\[ u_{H4} = \frac{2.5 \times 10^{-6} \times 1}{\sqrt{3}} H_0 \] (19)
\[ u_{F4} = \frac{2.5 \times 10^{-6} \times 1}{\sqrt{3}} F_0 \] (20)

Uncertainty of synthetic standard

\[ u_{HC} = \sqrt{u_{H1}^2 + u_{H2}^2 + u_{H3}^2 + u_{H4}^2} \] (21)
\[ u_{FC} = \sqrt{u_{F1}^2 + u_{F2}^2 + u_{F3}^2 + u_{F4}^2} \] (22)

Extended measurement uncertainty

\[ U_H = k \times u_{HC} \] (23)
\[ U_F = k \times u_{FC} \] (24)

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.

Table 1. Measurement uncertainty in the vertical direction.

| 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 \( u_{HC} \) | 2 | 4.036 |
| Extended measurement uncertainty \( U_H \) | 2 | 8.073 |
| Relative measurement uncertainty \( U_{HR} \) | / | 4.0% |

Table 2. Measurement uncertainty in the horizontal direction.

| 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 | 1.2 |
| The uncertainty component introduced by horizontal resolution \( u_{F3} \) | \( \sqrt{3} \) | 28.9 |
| The uncertainty component caused by temperature change \( u_{F4} \) | \( \sqrt{3} \) | 0.0 |
| Synthetic measurement uncertainty \( u_{FC} \) | 2 | 29.0 |
| Extended measurement uncertainty \( U_F \) | 2 | 58.0 |
| Relative measurement uncertainty \( U_{FR} \) | / | 1.2% |

Both horizontal and vertical measurements require multiple measurements. The simulated image of measurement is selected as shown in Figure 5. In this coordinate system, the X-axis is cycled, and Y-
axis is span about the height of the measurement sample. From the measurement uncertainty analysis aspect, the vertical direction’s measurement uncertainty is introduced by the superior standard and the measurement repeatability. Meanwhile, the horizontal resolution leads to the horizontal measurement uncertainty. The horizontal measurement results are more accurate than the accuracy results, but the vertical measurement is relatively difficult and more easily inaccurate.

![Figure 4. The simulation diagram is used for the measurement.](image)

6. Conclusion

The step profiler is a common micro and nano detecting equipment. It has high resolution and can realize fast imaging of micro and nano lines’ width and spacing. We study that the measurement uncertainty of step profiler, which has important reference value for analyzing and evaluating the equipment’s indication error, to obtain the final extended uncertainty, the important is to control the data in micro-nano measurement. Further improvement of horizontal resolution and vertical repeatability for measurement results can improve the performance of the equipment.

References

[1] Fei Yetai. Error theory and Data Processing. (2017) Machinery Industry Press, Beijing.
[2] Huijuan Yu, Qiangxian Huang, Rui Zhang, and so on. (2016) A scanning probe microscope for surface measurement in nano-scale, nanoscience and nanotechnology, vol.16:6011-6017.
[3] Gaoliang Dai, T.Dziomba, F. Pohlenz, and so on. (2010) Metrological AFMs and its application for versatile nano-dimensional metrology tasks. Pro. of SPIE, vol.7544:75446-1-75446-8.
[4] Attota, Ravi Kiran. (2019) Through-focus scanning optical microscopy applications. Pro. of SPIE, vol.11056:1-7.
[5] Gajendra S. Shekhawat, Vinayak P. Dravid. (2005) Nanoscale Imaging of Buried Structures via Scanning Near-Field Ultrasound Holography, Science, Vol. 310, No. 5745:89-92.
[6] HU Yaling, HU Zhengyi, Tian Puqiang, and so on. (2017) Using a level meter when testing the thickness effect of improved accuracy, Compilation of 2017 electronic glass Technical papers,139-144.
[7] Eberhard, Thomas, Roland, and so on. (2019) Scale spanning subnanometer metrology up to ten decades. Pro. of SPIE, vol.11056:1-7.
[8] Huang, Yu, Zhu, Ruogua, Dai, Bizhi. (2005) Present state and development of nanometrology. Proc. of SPIE Vol. 5635:486-492.
[9] L Koenders, R Bergmans, J Garnaes, and so on. (2003) Comparison on Nanometrology: Nano 2-Step height, Metrologia,40(1A):04001.
[10] Peter Ekberg, Lars Mattsson. (2018) Traceable X, Y self-calibration at single nm level of an optical microscope used for coherence scanning interferometry, measurement science and technology,29:1-12.
[11] Han Zhiguo, Li Suoyin, Zhao Geyan, and so on. (2015) Adjusting and Repairing of General Troubles for Contact Profiler. 11:43-47.
[12] JJF(Hu) 59-2018. (2018) Calibration Specification for Micro/Nano-Step Height/Depth Standards[S].