Improvement of quantitative depth evaluation for diffraction-limited microgroove using LED light source

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Abstract. The quality control of microgrooves is extremely crucial to ensure the performance and stability of microstructures and improve their fabrication efficiency. In our previous work, a novel optical inspection method to detect the depth of microgrooves with a width less than the diffraction limit was proposed. However, the occurrence of speckle noise due to high coherence of laser source is a dominant factor to increase the measurement noise for depth evaluation. In this paper, a Linnik microscopic interferometer measurement system using LED source and related bandpass filter was developed. The experiments based on LED illumination were carried out and compared with experiment results by laser source. It is found that the speckle noise is obviously reduced by LED illumination and the accuracy of calculated depth distribution for diffraction limited microgroove is improved.

1. Introduction
In recent years, we have experienced an increase in the need for the mass production of microstructures with high precision in the semiconductor industry and precision engineering industry [1]. On the surface of these microstructures, the microgroove is one of the essential micro-shape components and acts as the key functional element. In order to reliably fabricate these microstructures with high accuracy, quantitative dimensional measurements for microgrooves play a vital role. This research concentrates on the depth measurement of microgrooves, which is one of the most important quality control factors.

The conventional optical interferometry based on phase change is widely applied for depth measurement due to its non-destructive, high throughput and high vertical resolution. The depth of microgroove by conventional method is proportional to the practically detected far-field phase difference (\(\theta\)) between the upper flat surface and the bottom. Nevertheless, the conflict between the miniaturization of microstructures and diffraction limit largely restricts the application of conventional optical method. For diffraction limited microgroove, width of which is less than diffraction limit, only a minute change in the far-field phase difference can be observed owing to the low lateral resolution problem of conventional optical interferometry. To address this problem, some super-resolution technologies have been developed to achieve depth measurement of unresolved microstructures [2]. However, further studies on the reflected optical response from the bottom of diffraction-limited microgroove and methods by which to reconstruct the depth information in a more practical manner are...
urgently required. In our previous work, a novel optical depth measurement method for diffraction limited microgroove was analysed by laser illumination [3-4]. Because the laser has high coherence, the occurrence of speckle noise, which is an intensity pattern produced by the mutual interference of a set of wavefronts, dramatically reduce the measurement accuracy for depth measurement. Hence a Linnik microscopic interferometer measurement system using LED source and bandpass filter was established to improve the measurement accuracy of quantitative depth evaluation for diffraction limited microgrooves in this investigation.

2. Proposed optical depth evaluation for diffraction limited microgroove

The proposed optical depth measurement method connects the depth of diffraction-limited microgrooves with the near-field phase difference ($\theta$) calculated from practical far-field optical observations. Figure 1 is the schematic of far-field optical wave forming mechanism. According to optical imaging theory, the far-field response is formed by the convolution of the complex amplitude of the near-field response from microgroove and the point spread function (PSF). In the case of microgroove with widths much larger than diffraction limit, the detected far-field optical wave totally originates from the bottom part, and $\theta'$ is equal to $\theta$ and contains accurate depth information. Nevertheless, for diffraction-limited microgrooves, there are also contributions from the upper flat surface in the far-field plane because of the PSF. As a result, $\theta'$ shrinks compared to $\theta$ and cannot accurately reflect the depth information. In addition, from Fig. 1(b), it is found that for diffraction limited microgroove, the practical detected amplitude ($A_3$), $\theta'$ and amplitude from upper flat surface ($A_1$) obey the cosine law, with which $\theta$ and the corresponding depth can be calculated. Both $A_3$ and $\theta'$ are practically observable, and $A_1$ is given by

\[
A_1(x_i) = \sum_{i=1}^{n} A_{ij} = \frac{A_{\text{uniform}} \times \left[ \int_{-\infty}^{x_i} \text{asf}(x)dx + \int_{x_i}^{+\infty} \text{asf}(x)dx \right]}{\int_{-\infty}^{+\infty} \text{asf}(x)dx}
\]

where $A_{\text{uniform}}$ is the amplitude reflected from the uniform flat surface without microgroove area and can be practically observed. $x_i$ is the lateral distance between the far-field detection position and microgroove edge. The calculated $A_1$ is substituted into the retrieve algorithm for obtaining the reflected near-field optical response ($\theta'$), shown as Eq. (2).
3. Developed Linnik measurement system using LED and experiment verification

A schematic of the developed Linnik microscope interferometry system is illustrated in Fig. 2. Light from a cold white LED light source (MCWHLP1, 2350 mW, Thorlabs) passes through an aperture and a bandpass filter (FLH532-10, CWL=532 nm, FWHM=10 nm, Thorlabs). Figure 3 shows the spectrum of LED light source and the transmission of filter. Calculated by Eq. (3), the coherence length (L) is 28.3 μm, which is twice the maximal detectable depth on test surface by developed measurement system.

\[
L = \frac{\text{CWL}^2}{\text{FWHM}}
\]  

Then the light passes through a collimating lens (lens 1) and the second aperture. After that, a long focal length lens (lens 2) and two identical objective lenses (#46-144 Plan Apo, N.A.=0.28, Mitutoyo) are mounted. If the separation of lens 2 and objective lens is approximately equal to the sum of their focal lengths, the plane wave incidence will irradiate the sample and reference mirror. A shutter is set in the reference path. When the shutter is closed, measurement system is just an imaging system and only the reflected beam from sample is collected by the CCD camera (8 bits). When the shutter is opened, two beams reflected from the sample and the reference are combined at the beamsplitter and create interference fringes and are finally captured by the CCD. The sample is mounted on a three-axis stage, and the reference mirror is mounted on a PZT actuator to achieve phase shifting control. The theoretical magnification power of this measurement system is 20, and the diffraction limit is 1159 nm.

Figure 4(a) presents a schematic of the test standard silicon sample (nanoimprint trial mold DTM-2-1, Kyodo International Incorporation). On the surface, there is a uniform flat area and grating microgroove area. For each microgroove, the nominal width, depth, and pitch are 1, 1, and 2 μm, respectively. The nominal width is less than the diffraction limit of developed measurement system (1159 nm). The measurements and data processes are as followings. Firstly, with shutter closed, the image including uniform flat area and microgroove area was captured by the CCD. Figure 4(b) is the observation by laser source in our previous research, and observation by LED source in this investigation is illustrated in Fig. 4(c). It is found that the speckle noise is obviously reduced by LED illumination. The average amplitude value of uniform flat area is regarded as \(A_{\text{uniform}}\) in Eq. (2) to calculate \(A_1\), and the direct observation of microgroove area denotes the square of \(A_3\). Next when the shutter was turned on, four interferograms with \(\pi/2\) phase shifting were collected to compute \(\theta'\). Finally, \(A_1, A_3\) and \(\theta'\) were
substituted into the proposed retrieve algorithm, according to Eq. (3), to compute the near-field phase differences for microgrooves. The $k$ in the Eq. (2) is selected as 3 in this experiment.

![Schematic of test standard grating microgrooves on silicon sample.](image1)

![Observation with shutter closed by laser.](image2)

![Observation with shutter closed by LED.](image3)

**Fig. 4** Schematic and observations for test standard sample.

**Fig. 5** is the calculated two-dimensional depth distribution for microgrooves with a FOV of 16 μm × 8 μm. The overall quality of calculated depth distribution is evaluated by residual errors between the calculated bottom depths and the nominal depth (1000nm), and the evaluation is carried out by computing the average value and standard deviation of residual errors. As shown in Table 1, the average value and standard deviation of residual errors by LED source decrease obviously, which is a strong indicator for the feasibility of proposed method and the superiority of LED light source.

![Calculated two-dimensional depth distribution for the microgrooves.](image4)

**Fig. 5** Calculated two-dimensional depth distribution for the microgrooves.

| Tab.1 Improvements of residual errors of calculated depths by LED source. |
|---------------------------------|-------|-------|
| Average value [nm]              | Laser | LED   |
|                                 | 21.57 | 0.11  |
| Standard deviation [nm]         | 25.22 | 16.95 |

### 4. Summary

The method demonstrated in this paper provides a new methodology for quantitative depth evaluation of diffraction limited microgrooves. A Linnik interferometry measurement system using LED source and bandpass filter was developed. The experiment results show an observation with lower speckle noise and a dramatic decrement of calculated residual depth errors of bottom part for diffraction limited microgrooves by LED illumination.

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