論文の内容の要旨

論文題目　Research on optical depth-measurement of functional microstructures beyond the diffraction limit
（回折限界を超えた微細機能構造の光学的深さ計測に関する研究）

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Functional microstructures, produced with a deterministic pattern of geometric features designed to give a specific function, have received significant scientific interest over the past years, mainly because it has played a decisive role in the development of many industrial fields, such as semiconductor industry, medical and biochemical applications, automotive industry and telecommunication area, etc. Furthermore, a trend towards miniaturization of functional microstructures can be observed, particularly at a micro- and nanometer scale. As critical dimensions are scaled down, the functional exploitation of several physical phenomena becomes more and more important, e.g. adhesive surfaces, super-hydrophobic surfaces, subwavelength structured surfaces, microfluidics system and solar cell surfaces, etc. On the surface of these functional microstructures, the microgroove structure, having an aperture size of a micro- and nanometer scale with high aspect ratio, is one of the essential micro-shape component and acts as the key functional element, such as micro U-shape cavities of optical sensors, nano hole arrays of solar cell surfaces, microchannels of microfluidics systems and hydrophobic microgroove structures, and so on. In order to reliably fabricate these functional microstructures, the quality control of microgroove based on dimensional metrology is gaining importance. Especially, the miniaturization process of functional microstructures and the rapid progress of manufacturing technologies are driving an imperious need of dimensional micro and nano metrology with high accuracy. Among the various quality control factors, this research focuses on the depth measurement of microgrooves, which is one of the most challenging tasks.

The conventional depth evaluation methods mainly include stylus profilometry, scanning probe microscopy (SPM), cross-section scanning electron microscopy (SEM), scatterometry, confocal laser scanning microscopy (CLSM) and optical interferometry. Although stylus profilometry and SPM are versatile and well established, there are limitations related to measurement speed and potential surface damage. Cross-section SEM has the advantages of relatively high throughput and the resolution with nanometers level, whereas the technology requires the vacuum condition for measurement and obviously destroys the sample. For all optical metrologies, the non-contact nature and high potential of in-process measurement are clear merits. Scatterometry is a promising technology for quality control with fast speed and astonishing accuracy, however, this method only can be applied to overall evaluation for periodic gratings. Compared to scatterometry, CLSM and optical interferometry can output the depth information with respect to position. Furthermore, compared to CLSM, optical interferometry has the important property of higher sensitivity irrespective of magnification, not requiring a scanning process, and a better axial resolution for depth measurement. However, due to the significant errors of the measured depths, CLSM and optical interferometry cannot be applied to the depth measurement of microgrooves, width of which is fewer than the diffraction limit. In this PhD thesis, the microgroove with width fewer than the diffraction limit is named by diffraction-limited microgroove.

In order to solve these problems, the goal of this thesis is to develop a novel optical depth measurement method, which (1) enables the quantitative evaluation of the diffraction-limited microgrooves, having an aspect-ratio of 1, on different materials, with an accuracy of 10%, (2) is capable of the individual difference evaluation of each microgroove, and (3) has a depth measurement range optically greater than half of the incident wavelength, without the phase ambiguity problem.

The proposed method, called Far-field-based Near-field Reconstruction Depth Measurement (FNRDM), connects the depth information of diffraction-limited microgrooves with the near-field phase difference, which can be calculated from practical far-field optical observations rather than directly measured by specialized equipment, i.e., near-field scanning optical microscopy. By the FDTD method, the theoretical analysis was performed to demonstrate the validity and the detectable depth of FNRDM when measuring the diffraction-limited microgrooves. Furthermore, the practical applicabilities of FNRDM were discussed, including materials, internal shapes, noise conditions, grating structures and microhole structures. The simulation results show that: (1) the depth of a fine 200-nm-wide and 300-nm-deep microgroove can be measured by FNRDM, with an accuracy of 8 nm (3%) beyond the diffraction limit of 540 nm. (2) When the scattering light from the edges of microgrooves becomes the dominating contribution of the synthetically observed optical wave, FNRDM cannot be applied to evaluate the depth. It is found that, by FNRDM, the measurable aspect-ratios are 5 for the 200-nm-wide microgroove, 3 for the 100-nm-wide microgroove and 1 for 50-nm-wide microgroove, beyond the diffraction limit, by using the wavelength of 488 nm. (3) As long as the optical wave from the bottom surface is radiated to the far-field, FNRDM has the potential to evaluate the depth information. (4) Under the noise condition, although the accuracy of depth measurement is greatly influenced by numerical aperture, both a 200-nm-wide microgroove with an aspect ratio of 1.5 and a 100-nm-wide microgroove with an aspect ratio of 2 can be quantitatively evaluated with less than 10% error by using imaging objective with numerical aperture of 0.95 and the wavelength of 488 nm (the Rayleigh criterion = 313 nm). (5) When using FNRDM to measure the depth of grating structure, a modified equation for calculating the amplitude of the top surface was proposed to ensure the measurement accuracy. Furthermore, it is found that when the pitch of the grating structure is much larger than the diffraction limit of applied imaging system, each microgroove of the grating can be regarded as an isolated element, and the depth can be measured as the case of an equally single microgroove. (6) When measuring microhole structure by FNRDM using linear polarization, the depth of a microhole with 200-nm in diameter and 300-nm in depth can be quantitatively evaluated, with an accuracy of 10 nm (3%), beyond the diffraction limit of 313 nm.

Then, a measurement system based on low-coherence illumination was developed to inspect the required far-field observations of the proposed FNRDM method. Besides the feature of low-coherence illumination, the designs of this measurement system also include an infinite corrected imaging system, a Linnik interferometer, an incident plane wave unit and an optical cage system. By comparing the height maps of a same flat surface on transparent polymer by a laser-based setup and the developed system based on low-coherence illumination, it is found that the spatial uniformity and accuracy of images by the low-coherence illumination are substantially better than the laser source. In addition, through the evaluations of temporally topography histogram of point measurement and spatial topography histogram of area measurement, it is demonstrated that the measurement system allows for spatially sensitive optical path-length measurement (2.24 nm) and temporally sensitive optical path-length measurement (0.83nm).

Next, the nanochannels on a microfluidic sample (COC, nominal width = 300 nm, depth = 110 nm) were measured to verify the validity of FNRDM. Both a AFM and the developed measurement system were used to measure this sample. There are some experiment results: (1) the overall evaluation of measured depths of nanochannels in the same area are 67 nm by conventional optical interferometry, 107 nm by FNRDM and 114 nm by AFM measurement, respectively. (2) The same trend in depth variation of different nanochannels between FNRDM and AFM was confirmed. (3) The repeated experiments by FNRDM were performed, and the standard deviation is approximately 2 nm. According to the experiment results, our method has the advantages of greatly improved accuracy over conventional interferometry and enables the individual difference evaluation of each nanochannel, which is not possible with scatterometry. It is demonstrated that FNRDM and the developed measurement system can measure the depth of 300-nm-wide nanochannels beyond the diffraction limit (772 nm) with an accuracy of less than 10%.

However, similar to other optical depth measurement methods based on phase change, FNRDM using a single wavelength have the limitation: the measured depth which is optically greater than half of the incident wavelength subjects to the phase measurement ambiguity. In order to solve this problem, a noise-immune dual-wavelength interferometry was proposed. Using the noise-immune dual-wavelength interferometry, not only the depth measurement range can be extended, but also the noise level can be dramatically decreased to that in a single-wavelength phase map. Combined with the developed measurement system based on low-coherence illumination, a dual-wavelength interferometer unit (λ = 532 nm and 520 nm) was inserted to meet the requirements of practical measurements. Two experiments of measuring the gratings on different materials were performed. The experiment results showed that: (1) the 1000-nm-wide microgrooves, having an aspect-ratio of 1, with width less than the diffraction limit (1159 nm and 1132 nm) of develop measurement system on a silicon surface, can be quantitatively evaluated with an accuracy of less than 5% by the combination of FNRDM and the noise-immune dual-wavelength interferometry. (2) The 700-nm-wide microgrooves, having an aspect-ratio over 0.5, with width less than the diffraction limit (772 nm and 755 nm) of develop measurement system on transparent polymer surface, can be quantitatively evaluated with an accuracy of less than 10% by the combination of FNRDM and the noise-immune dual-wavelength interferometry. The combination also has a potential of measuring the depth of diffraction-limited and steep microgrooves with high accuracy.

Simultaneously, a novel method using a Fluorinert droplet was also presented to achieve the phase unwrapping. This method includes the generation and combination of two phase maps under an air condition and a droplet condition. When the two phase maps are combined, the measured depths are equivalent to those measured by a longer wavelength based on the refractive index difference. In order to achieve the droplet-based phase unwrapping method, a one-shot interferometry based on the Fourier Transform method, an auxiliary horizontal observation setup with high speed camera and a Fluorinert liquid with unique properties were presented. Based on the RCWA simulation, the numerical analysis was performed to verify the applicability of the droplet-based phase unwrapping method. In the case of diffraction-free microgrooves, the simulation results show that the droplet-based phase unwrapping method enables the depth evaluation of a 1000-nm-wide and 300-nm-deep microgroove with an accuracy of 16 nm (5%), without the phase ambiguity problem, using the wavelength of 488 nm. In the case of diffraction-limited microgrooves, the FNRDM method was combined to calculate the near-field phase difference. The simulation results suggest that by the droplet-based phase unwrapping method and FNRDM, the depth of a 300-nm-wide microgroove, with an aspect-ratio of 1, can be quantitatively evaluated with an accuracy of 24 nm (8%), without the phase ambiguity problem, beyond the diffraction limit of 540 nm, using numerical aperture of 0.55 and the wavelength of 488 nm. The proposed method enables the phase unwrapping by using only single-wavelength illumination, has a high temporal resolution and requires significantly less computational work than other least-squares integration technologies.

Overall, the highlights of our work lie in: (1) using only the far-field observations, the depth of diffraction-limited microgrooves can be quantitatively evaluated with an accuracy of less than 10%, which is not possible by conventional optical depth measurement method based on phase change. (2) The proposed method is capable of the individual difference evaluation of each diffraction-limited microgroove, which is not possible with scatterometry. (3) The depth measurement range has been extended to optically greater than half of the incident wavelength without the phase ambiguity problem, which makes it possible to measure the depth of diffraction-limited and high aspect ratio microgrooves. (4) Not only the silicon surface, but also the transparent polymer surface can be measured. (5) Due to the clear merits of optical metrology and a dependence of only far-field observations, the proposed method has a high potential of in-process measurement. Therefore, our work brings a progress to optically three-dimensional imaging of diffraction-limited microstructures and motivate the studies in bio-inspired functional surfaces, precision engineering, medical and biochemical applications, etc. Furthermore, the results of this study have the potential to impact various industries where high-precision-microstructure mass production is crucial, such as semiconductors and microsystem techniques. We think these findings will be of great interest to researchers in dimensional micro and nano metrology, and particularly to researchers working on optically depth measurement and super-resolution technology