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Study of Microfabrication and Error Calibration for Multilevel Diffractive Optical Element by Thin Film Deposition*

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Abstract

Photolithographic patterning and thin film deposition were used for manufacturing multilevel diffractive optical element(DOE). Fabrication errors and its affecting factors were analyzed for multilevel DOE in this paper. Calibration method was come up with to modify alignment error. It was proved by actual manufacturing process that this method is available for aligning positioning error.

Key words: Photolithography, Thin film deposition, Multilevel DOE

1 Introduction

Multilevel DOE has higher diffraction efficiency than binary optical element (BOE) such as Dammann grating etc. Its designing idea is found on the base of sampling discretion of electric signal. Method of discretting continuous relief has to be used for the sake of difficulty to manufacture the continuous relief by IC technology, so as to approximately approach the continuous relief of DOE using multilevel step. The more the number of level is, the more high of the diffraction efficiency, and results of approaching is better. But the manufacture is difficult increasingly in the meantime. Repeated operation is required in the process of photolithography. Therefore, the accuracy of repeated lithographic patterning is one of

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the key technologies for fabrication of multilevel DOE.

Someone has ever discussed the manufacture error about DOE by computer simulation[1]. Because the manufacture is affected by many factors such as operator, equipment and environment in process of photolithography and ion beam etching. It´s very difficult to analyze the manufacturing accuracy clearly only in the view of theory due to so many effects. Considering a certain limitation for computer simulating the factors affecting accuracy in actual operation is analyzed by example of manufacturing DOE with 4 levels in this paper. Calibration method and procedure has been introduced. A compensation method is put forth to align depth error and lateral positioning error of steps. It´s simple and practical in actual manufacturing process and also suitable to other microfabrication application.

2 Discussion of manufacturing process

2.1 Comparison of two different manufacturing processes

The geometry thickness of coating layer is determined by the following formula

$$d = \frac{\lambda}{2^m(n-1)} \quad (1)$$

where

n ——material refractive index;

m ——repeat lithographic times($m = 1, 2, 3, \cdots$)

Table 1 Comparison of two operating orders

orders	2# (fine line) mask→1# (wide line) mask	1# (wide line) mask→2# (fine line) mask
advantages	1. easy to ensure lateral size positioning accuracy 2. after finishing first time 1# lithography-coating, surplus resist is easy to be cleaned due to the small depth of staircase	1. easy to ensure accuracy of staircase depth 2. producing small height error because of the thin layer thickness of the next step.
disadvantages	1. easy to produce height error during the next step 2. Difficult to align at the beginning operation. If the lateral error produced, large height error occurs during the next recycle.	1. difficult to control the lateral alignment accuracy 2. surplus resist is difficult to be cleaned for the next step

Detailed fabrication process isn´t introduced at here because it had been introduced by some papers. Two masks are needed for the DOE fabrication process. Feature size and number of annular of the second one (2# mask) are half of the first one (1# mask). There are two operating orders. One is repeating lithography and coating from 1# wide line mask to

2# fine line mask the other is from 2# fine line mask to 1# wide line mask. Their advantages and disadvantages are compared as table 1.

2.2 Calibration of coating thickness

Coating thickness is controlled by quartz crystal oscillator. Oscillating frequency is displayed by frequency meter. The coating thicness calibration can be carried out by the following formula

$$\Delta f = k f_0^2 n d \qquad (2)$$

where

Δf —— corresponding frequency difference of digital frequency meter between two thickness

k —— coefficient

f_0 —— initial coating display value of the frequency meter

Calibration procedure can be arranged as the follows

- Coating SiO_2 layer with any thickness, operator writes down the initial value and the end value of frequency meter, then Δf can be obtained.
- Measuring the corresponding optical thickness of SiO_2 layer nd by interfere-spectrometer.
- The value of k can be get by Δf, f_0 and formula(2).
- Calculating actual optical thickness nd by formula (1).
- Writing down the frequency at the time of starting coating and regarding it a f_0.
- Δf corresponding the required thickness which can be derived in terms of formula (2).
- Stopping machine while the display value reaches $f_0 - \Delta f$.

3 Processing error and affecting factors

The relief structure of the designed DOE is like Fresnel zone plate (consists of many concentric annuluses with different height of staircase), but the curve shape is different. The wave plane of Fresnel zone plate is parabolical, but aspherical curve is fitted by polynomial for the DOE. The detail manufacturing process was reported by some references[3~5] that two times recycles operation have to be adopted from photolithography patterning to thin film deposition. The error in all process can be classified into two parts. One is growing up error, and the other is alignment error.

The growing up error includes depositing depth changed through all surface of element systematically and random fluctuation of step depth. The former mainly affected by the way of controlling depth during thin film deposition process. It can be vanished by using high accuracy monitoring method such as quartz crystal oscillation in which the error can be controlled to about 0.5 nm. It will be introduced behind. The latter is mainly affected by working environment and roughness on the surface of substrate. It can be reduced or overcome in certain degree by the following method

· Improving controlling accuracy of temperature and humidity for supercleaned room.

· Controlling vacuum chamber temperature accurately (Temperature will affect coating uniformity).

· Reducing roughness of substrate surface.

Alignment error includes the manufacturing error from mask itself. The used four masks were all made by E-beam lithography which has a very high accuracy with a minimum spot size of 0.1 μm. Thus, it's too little to be considered at present. The lateral positioning error has a main role in alignment error, where it's vital to the accuracy of DOE. It often occurs during the transfer of the pattern from the original mask to the final mask on the substrate due to accumulated aligning error. Specifically, incorrectly exposed or developed photoresist in the lithographic process will alter the linewidth of the annuli and thereby the duty cycles in each grating period. Obviously, the duty cycles in the outer fine structued zones with feature size are more heavily affected than those in the inner coarse zones. It should discussed in detail in this paper.

4 Controlling and modifying of alignment error

The diffraction efficiency is directly influenced by the alignment error and ion beam etching error. Therefore, modifying them is very important in the whole manufacturing process.

4.1 Effect of exposure intensity

If over exposing, the width of transparent part of the pattern will be large using positive photoresist. The width among singular annular will be reduced after ion beam etching. If under exposing, the width of the transparent part will be narrow, and leads to staircase widening. Therefore, the appropriate exposure intensity should be selected according to the actual thickness of photoresist. Linear relationship between intensity and developing depth & time were presented[5]. When required developing depth is selected, the corresponding exposure intensity will be determined according to its linear relation. The linewidth error can be controlled in the range of 3μm.

4.2 Aligning repeated photolithographic error

The repeated photolithographic error is also called lateral positioning error. The total number of annular N of used masks from first to second are 112, 224 respectively. When eccentric occurs between the mask and the substrate, the Moire fringe will be produced along radial for the sake of interlaces from the annulas on the two layers. Particularly in the part of high density of annulas, the fringes are very clear. Its feature is that number of fringes increase and is getting to approach to Y axis while apart from X axis with the eccentricity and direction of connecting line between two centers, the number of fringes and its angle position maintain unchanged while any mask is revolved around the center of substrated. When the centers of both mask and substrate are overlapped completely (absolutely concentric), there are no Moiré fringe produced at this moment. According to this phenomenon, judgment can be made that there is no positioning error occurred in this case.

Alignment by virtue of manual or automatic can be carried out taking advantage of this feature. Moiré fringe is received by photodetector and transferred to digital pulse signal by A/D. Every pulse corresponds to a fringe. A counter is used to record the number of pulses. The number of moving fringes in sight can be known according to the recorded value. The corresponding eccentricity can be calculated by Moiré fringe equation. Then, transferred it to analogue signals by D/A and sent it to micromechanical to control the three dimensional workplate adjusting the error along, X, Y and θ. The alignment of eccentricity can be put into reality. The positioning error produced by misalignment is vanished consequently by this way. When the feature size of the pattern is 10μm, the accuracy of repeated lithography should be within submicrometer. In this case, the automatic alignment can be realized using PDT piezoelectric micromechanical. If the feature size is over 10μm, the required accuracy is within micrometer. The alignment can be carried out by virtue of feedback controlling and adjusting mechanical, and observed from CCD camera and monitor.

5 Testing results and conclusion

Radius of the manufactured DOE with 4 level is different from 1.52mm for minimum

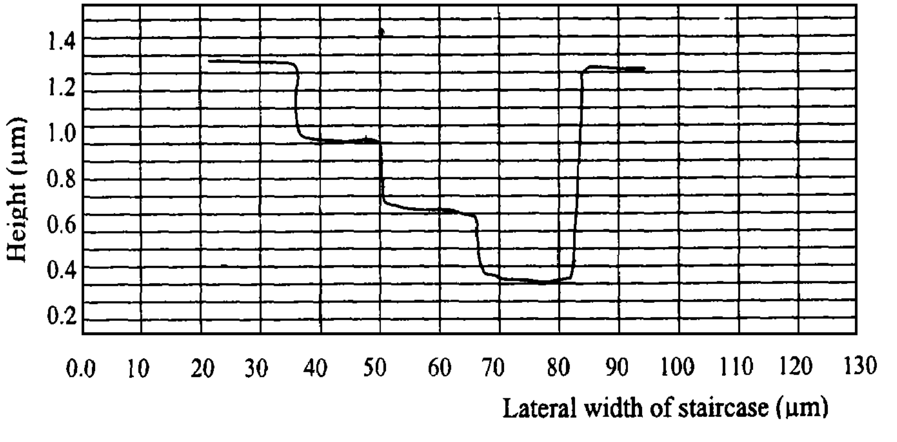

Fig. 1　Surface profilometer trace of the inner zone level

and 19.96mm for maximum. The mentioned alignment method of Moiré fringes is used to manufacture the 4 levels DOE. Depth and width of the staircase are meausred by Talystep profilometer. Measuring results are shown as Fig. 1. It can be seen from the diagram that there are only a few changing for the sizes in two directions. Relative position error is less than 4.2%. There is a little sharp peak convex on eighth step because residual photoresist on the part of transparent was not cleaned completely before third times repeated lithography discovered under microscopy. It can be known from further testing that it has little effect on imaging aberration.

The measured actual diffraction efficiency is as high as 65.4%, which has a little distinction compared with the theoretical value 82%.

Therefore, the following conclusions can be drawn

· The manufacture error of multilevel step DOE consists of ion beam etching error and alignment error, where the alignment error is larger and, it affects diffraction efficiency of DOE greatly.

· Lateral positioning error is the main factor influencing diffraction efficiency in alignment error.

· It was proved by reality that the modification method using Moiré fringe to compensate the eccentricity is practical and available.

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薄膜沉积多级衍射光学元件的微型制作与误差标定的研究

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摘　要　应用光刻和薄膜沉积技术,制作了多级衍射光学元件。对制作误差和影响误差的因素进行了分析。给出了改善对准误差的标校方法,并在实际的多级衍射光学元件制作过程中得到验证。

关键词　照相制版　薄膜沉积　多级衍射光学元件

中图分类号　O484.41　　文献标识码　A

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