Monitoring of reactive ion etching of computer-generated holograms by specular spectroscopic scatterometry

A.S. Konchenko¹, V.P. Korolkov¹, A.I. Malyshev¹, A.R. Sametov¹

¹Institute of Automation and Electrometry SB RAS, 630090, Novosibirsk, Russia
²Novosibirsk State University, 630090, Novosibirsk, Russia
Tel.: + 7 [383] 333-3091 E-mail: victork@iae.nsk.su

Abstract
Specular spectroscopic scatterometry is used to measure zeroth-order diffraction intensity spectrum of white light reflected at a fixed angle from diffractive structure. Extremes location in the spectrum depends on profile depth. However, chromium film used as a mask at reactive ion etching of fused silica substrate at hologram fabrication contributes unknown phase shift to the reflected light. The paper is devoted to the behavior of the phase shift during dry etching and checking an applicability of the specular spectroscopic scatterometry for measurement of binary amplitude-phase grating at iterative monitoring of the etching process.

Keywords: Specular spectroscopic scatterometry, etch depth measurement, computer-generated holograms, reactive ion etching, amplitude-phase gratings

1. Introduction
Fabrication of binary phase computer-generated holograms (BPCGH) used for precision testing of aspherical optical elements [1] requires high uniformity of groove depth on hologram surface. It is caused by necessity of uniform intensity modulation in interference pattern. BPCGHs of new type – diffractive Fizeau null-lenses (DFNL) [2] – are especially sensitive to uniformity of groove etch depth. The reason is they operate not only in transmission but also in reflection. Such holograms are much more sensitive to etch depth errors than ones operating in transmission. Taking into account a wide variety of periods and a large size of BPCGH structures the control of groove depth is associated not only with significant amount of work but also with the practical impossibility of on-line profilometric depth measurement at groove period of the order of several microns. There is so called specular spectroscopic scatterometry (SSS) method which is based on measuring a zeroth-order diffraction response at a fixed angle of incidence and multiple wavelengths [3]. The method was developed for submicron critical dimension measurement in semiconductor manufacturing. Our version of the method [4] is taking into account the specificity of surface relief of BPCGH which is quite different from typical relief of integral circuits. Periods of BPCGH microstructure vary from 1-2 micron to hundreds of microns. Profile depth is typically about 500-700nm. Total dimensions of BPCGH can exceed 200mm. We checked our method for measurement of phase holograms. However, during manufacturing BPCGHs it is necessary to measure profile depth of amplitude-phase diffractive structure because phase profile in fused silica substrate is made by reactive ion etching (RIE) through chromium mask. Phase shift of light wavefront at reflection from metal film changes reflection spectrum in zeroth-order diffraction. It makes more complicated an interpretation of the reflection spectrum for amplitude-phase gratings.

In the present paper we study the possibility of using the specular spectroscopic scatterometry for measuring the etch depth of amplitude-phase binary structures.

2. Specular spectroscopic scatterometry method
The measurement method for binary phase gratings is based on peculiarity of reflection spectrum. The optical path difference (OPD) appears between the light beams reflected from
ridges and grooves of the grating. OPD and the phenomena of two-beam interference occurs (Fig. 1, a). Total intensity of the light reflected in zeroth diffraction order depends on the OPD and has a periodic dependence on the wave number of the incident light (Fig. 1, b). The intensity of reflected light has local extremes when the OPD is a multiple of half wavelength.

Fig. 1. a - light reflection from binary phase grating, b - example of experimental reflection spectra from binary phase grating.

The OPD of light beams $\Delta l$ depends on the grating depth:

$$\Delta l = \frac{2H}{\cos(\alpha)},$$

And the reflected light intensity has its extremes at wavenumbers $k = \frac{1}{\lambda}$ satisfying the following condition:

$$k = \frac{m \cdot \cos(\alpha)}{4H}.$$

Hence, knowing the position of the reflected light spectra it is possible to determine the etch depth of the phase grating as follows [4]:

$$H = \frac{\cos(\alpha)}{4(N-1)} \sum_{i=1}^{N} \frac{1}{k_{i+1} - k_i}$$

3. **Amplitude-phase gratings**

During RIE process, it is necessary to monitor the profile depth in pause of etching. It helps to achieve required value for several iterations. The SSS method looks promising for the monitoring due to contactless principle and possibility to measure large hologram with wide range of groove periods for short time [4]. When SSS method is applied to amplitude-phase grating a part of the light reflects from bottoms of the grooves in fused silica substrate surface and the rest of the light reflects from the chromium mask where the additional phase shift $\phi_{Cr}$ appears (Fig. 2). This phase shift causes the shift of reflected spectrum extremes position $\Delta k$ (Fig. 3) and affects the depth measurement results. The figure also shows the constant additive intensity due to the reflection from backside of the substrate. This additive doesn’t affect the spectral position of extremes and doesn’t bring a considerable error to depth measurement. It just reduces signal/noise ratio.
To take the extremes shift into account at the grating depth measurement it is necessary to know the spectral dependence of the relative extremes shift. The extremes shift can be calculated with the theoretical equation using the values of chromium optical properties taken from handbook. However, optical properties of bulk chromium differ from the ones of thin Cr film [5]. Most articles, discussing the phase shift upon the reflection from metal surface, consider the case of light incidence from air to grating surface. In our case, it is better to measure spectra from backside of the substrate to avoid the influence of chemical changes of chromium layer due to the thermochemical laser writing [6]. In addition, this way of measurement lets us to exclude the mask thickness from the result depth. It is necessary to prove experimentally the independence of spectra shift on etching process duration because phase shift of light reflected from thin metal film depends on film thickness [7].

4. Experiment

For that purpose three amplitude gratings were made with chromium masks having period of 30 µm. The optical density of Cr film was about $D = 2.6$. The gratings were etched by RIE and after that the reflection spectra of amplitude-phase grating was measured. Further, a part of Cr mask was removed by liquid etching, and the spectra of pure phase grating with the same depth were measured. For each pair of spectra the value of relative extremes shift measured was determined according to the expression $\Delta_{extremum} = \Delta k \cdot (k_{i+1} - k_i)$, where $k_i$ and $k_{i+1}$ are the neighboring extremes of amplitude-phase grating spectra.

Figure 4 shows the experimentally obtained spectral dependences of $\Delta_{extremum}$ for the gratings with etch depths of 723 nm, 904 nm and 1330 nm. The experimental results were applied to the obtained extremes of amplitude-phase gratings. The difference between etch depths calculated for pure phase grating spectra and the restored spectra from amplitude-
phase grating with the obtained spectral dependences of $\Delta_{\text{extremum}}$ was about 1%. These results show the etching time does not affect the relative extremes shift at light incidence from the backside of the substrate. Such inaccuracy is satisfactory for monitoring the etch depth during manufacture process but the influence of Cr mask thickness on extremes shift should be studied for the full application of the method for the practical use.

Fig. 4. Experimental spectral dependences of extremes shift for different etch depths.

5. Conclusion

Specificity of application of specular spectroscopic scatterometry for monitoring the etch depth of computer-generated holograms at manufacturing process has been discussed. The main complexity of application is the necessity of measuring the depth of amplitude-phase gratings with chromium mask because it brings a phase shift to the reflected light. The influence of chromium mask on application of SSS method was experimentally studied. The results of the experiment have shown that the etching time does not considerably affect the relative value of extremes shift. The shift contributes error in profile depth measurement not exceeding 1%.

References