Diffractive grey-tone phase masks for laser ablation lithography

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Abstract

We investigated a fast parallel method for the fabrication of continuous profile structures in polymer surfaces using a XeCl excimer laser at a wavelength of 308 nm. The used quartz grey tone phase masks consist of diffractive gratings which diffract a fraction of the impinging light out of the aperture of the projection lens. The masks were generated by electron beam lithography and reactive ion etching on standard mask blanks. A variation of the duty cycle of the gratings enables us to control the transmitted zero order flux for different positions on the mask. Using this method, diffractive optical elements were ablated in polyimide films. For good optical performance, it was necessary to pre-compensate the response of the polymer film with regard to threshold and non-linearity. The structure profiles and diffraction efficiency of blazed gratings were measured and correlated with the correction parameters. © 2001 Elsevier Science B.V. All rights reserved.

1. Introduction

The recent development of low-cost high-power pulsed laser systems has led to a growing number of applications for the machining of surfaces by laser ablation. The generation of complex patterns can either be accomplished by scanning ablation tools, which are even capable of producing continuous topographies by varying the applied fluence on the substrate surface [1]. Due to the sequential nature of the method, the throughput is very limited. A parallel patterning of larger areas requires a set-up comparable to photo steppers, where a mask structure is projected onto the substrate surface [2]. One of the major problems of this method is the damage occurring in the chromium absorber structures of standard photo masks at high fluence levels [3]. Alternative technologies have been developed in the past to avoid this problem [4]. One of these techniques uses diffractive grating structures etched into a quartz mask blank to diffract the transmitted light out of the aperture of the projection optics (see Fig. 1). The projection of the patterned areas of the mask will therefore not cause any ablation on the substrate. Because no light is absorbed in the mask, no damage can occur even for extremely high fluence levels.

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Fig. 1. Set-up for the patterning of polymer surfaces by laser ablation using diffractive masks.

Our method combines the capability of scanning ablation tools to vary the ablated depth continuously with high throughput of projection methods. As a first application we patterned spin coated polyimide films (Durimide 7020™, Arch Chemical), which are known to give smooth surfaces when structured by laser ablation [5].

2. Mask design

The projection masks were designed for 308 nm wavelength radiation of a XeCl excimer laser using an 80-mm focal length projection lens at demagnification factors between 2 and 4. The grating pitch was kept constant at 3 μm, which provides a sufficiently high deflection angle of the diffracted light.

The transmitted fluence, i.e. the zero order diffraction efficiency of the mask structures depends on the duty cycle DC. The zero order efficiency $E_0$ of a phase grating can be calculated using simple scalar diffraction theory

$$E_0(\varphi, DC) = 1 - 4DC \cdot (1 - DC) \cdot (1 - \cos \varphi)$$

where $\varphi$ denotes the phase shift caused by the grating structures. For a refractive index $n$ the corresponding structure height $h$ is given by $h = \lambda/(n - 1) \cdot \varphi/\pi$. Fig. 2 depicts the result of such a calculation for quartz structures at a wavelength of 308 nm. For a 290 nm structure height and DC=0.5, the efficiency is close to zero. Here, the dependency on the grating height is not very pronounced; even for 250-nm deep structures will transmit only less than 6% of the incoming light. The diffraction efficiency was measured for test mask structures with 3 μm pitch and various duty cycles etched 290 nm deep into the quartz. The measured data are in good agreement with the calculations. This indicates that scalar diffraction theory is sufficient for our application.

In principle both regions of DC — the one between 0 and 0.5 or the one between 0.5 and 1 could be used. In our experiments only mask structures with DCs <0.5, i.e. with trenches narrower than the ridges where considered. However, this range is reduced by two effects. Firstly, very low DC values were avoided because these require the fabrication of narrow lines with good linewidth control. We
therefore restricted the gratings to line widths above 150 nm (DCs above 0.05). Secondly, the response of the used polyimide films reduces the useful linewidth range even further. Fig. 3 shows measured data of the ablated depth per laser pulse in the fluence range between 0 and 1 J/cm². Below a threshold value of 80 mJ/cm², no ablation occurs. The DC value that corresponds to the threshold depends on the maximum fluence. Assuming a maximum fluence of 800 mJ/cm², DCs resulting in efficiencies below 10% have to be avoided [5]. Thus, the useable DC range is limited to values below

Fig. 3. Ablated depth per laser pulse plotted as a function of laser fluence using a XeCl excimer laser and 20 μm thick spin-coated polyimide. The polymer response shows a threshold of 80 mJ/cm². For fluence values above the threshold, the response is curved. The data can be fitted by a square root function.
0.4 corresponding to 1.2 μm linewidth at 3 μm pitch. Above the threshold, the response of the polymer is non-linear. Using a square root function, a good fit to the data is achieved. This response curve together with the restrictions in the useable DC range was implemented into a computer code for the calculation of the mask exposure data.

3. Mask fabrication

For the fabrication of diffractive grey tone masks it was possible to use standard quartz mask blanks with 80 nm thick anti-reflective chromium and a 120 nm thick layer of PMMA e-beam resist. The exposures were carried out using a LION LV1 exposure system (Leica Microsystems Jena) at 2.5 keV electron energy. The Lion’s continuous path control mode, allowing for the exposure of straight or curved lines without any field stitching, is especially useful for this application. Each line of the diffractive structures was exposed with one single sweep of the electron beam. The line width was varied continuously by setting the defocus and line dose [6].

The developed patterns were etched in a Cl₂/CO₂ plasma into the Cr layer which served as a hard mask for the transfer into the quartz using a CHF₃/O₂ plasma. Fig. 4 shows an SEM picture of the mask structures for the fabrication of blazed optical gratings. The sudden jump in duty cycle of the line pattern indicates a step in the corresponding ablated profile.

Fig. 4. SE micrograph of a diffractive grey tone phase mask structures etched into quartz.
4. Results

A large variety of mask patterns were fabricated to test and optimise the described method. Fig. 5 shows profilometer scans of polyimide grating profiles with 50-μm pitch. The top curve was produced with a mask whose structures were calculated assuming a perfectly linear polymer response. The data exhibit plateaus at the grating ridges originating from the polyimide’s threshold. The middle curve shows the case, when the threshold is implemented in the mask data, but the curvature of the polymer response above threshold is neglected. As a result, the plateaus have disappeared leaving a clear convex curvature of the profiles. Only if the curvature is also taken into account, a nearly linear sawtooth like profile is obtained.

The diffraction efficiency of the blazed polymer gratings was measured using light from a He–Ne laser (632 nm wavelength). The efficiency of the different diffraction orders depends on the depth of the gratings which is proportional to the number of laser pulses (see Fig. 6). The gratings produced with the uncorrected diffractive mask show only a first order diffraction efficiency of below 50%. The gratings produced with corrected masks show first order efficiencies of greater than 60 and 70%,

![Fig. 5. Profilometer scans of blazed grating structures ablated in polyimide. The profile shape depends on the corrections for the polymer response curve shown in Fig. 3.](image_url)
Fig. 6. Diffraction efficiency of the blazed polyimide gratings plotted in Fig. 5 measured in transmission at 632 nm wavelength.

depending on the degree of correction. Moreover, the corrected gratings show clear resonances for higher diffraction orders when ablated to greater depths. This effect is known as over-phasing and occurs when the phase jump induced at the sharp edges of a blazed structure amounts to higher integers of $2\pi$. In case of the structures fabricated with the mask corrected for threshold and curvature, up to $4\times$ over-phasing can be observed. Thus, diffraction gratings with higher diffraction angles or Fresnel lenses with higher numerical aperture can be produced simply by increasing the number of laser pulses. Furthermore, more complex devices such as colour fan-out elements [7] could be fabricated.

In addition to simple linear gratings, more demanding structures such as Fresnel lenses were fabricated. The mask structures for such devices with rotational symmetry consists of concentric rings with a pitch of 3 $\mu$m. Fig. 7 shows the central zones of such a Fresnel lens. The waviness of the polymer surface is caused by the coherence of the illumination optics which was not matched to that of the projection lens.

By moving the sample and repeatedly exposing a Fresnel lens mask with a square aperture, two
dimensional arrays of diffractive lenses were stitched together with high fill factors (Fig. 8). Such arrays can be used as diffusers, homogenizers or beam shaping elements.

5. Conclusions and outlook

We have shown that the method presented here is suitable for the fast fabrication of 3-dimensional topographies in polyimide using laser ablation. The non-linearity of the polymer response can be precompensated in the mask design. The applied masks can be fabricated using standard photomask blanks. More complex patterns than the presented gratings and lenses could be generated using this method by encoding arbitrary grey tone patterns by using a dithering algorithm.

The generated polymer structures themselves are only of limited use in optical devices. A pattern transfer into glass or quartz e.g. by proportional etching techniques would open a larger spectrum of applications. The direct patterning by laser ablation of other materials like dielectrics or even metals could also be possible if sufficiently high laser fluences are applied.

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