Noise reduction in the recording of holographic masks in photoresist

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ABSTRACT

The lithography of gratings or structures using photoresist holographic masks is very critical, in particular when high selectivity etching processes were employed. In this paper we study the effect of the mask profile and of the phase perturbations during the holographic exposure in the noise of the photoresist masks. It is shown that the use of appropriate conditions of development and exposure may reduce significantly this noise allowing the recording of high aspect ratio structures and the use of selective deposition techniques.

Keywords: holographic optical components, photoresist, gratings

1. INTRODUCTION

Holographic recording in photoresist films is used to perform matrices for holograms and diffractive optics replication. The structure recorded in photoresist can be used also as a mask to transfer the pattern to the substrate by chemical or reactive ion etching. Using this technique new types of diffractive optical components and deep high spatial frequency structures may be realized\cite{1,2}. The main problem of this technique is the low contrast of the sinusoidal light pattern that makes the development process very critical. Excess of development will remove the photoresist mask completely. By the other hand, if the selectivity of the etching process is very high, any residual photoresist on the substrate hinders the etching, amplifying small defects of the photoresist mask. Figure 1 shows examples of such defects in lithographed structures due to small residues of photoresist.

Figure 1 – Examples of defects in the structure lithographed by RIE using holographic photoresist masks: (a) in a film of de a-C:H and (b) in InP substrate.

The quality of holographic photoresist mask depends on several parameters such as cleaning of the substrate, homogeneity of the thickness of the photoresist film, intensity distribution of the light pattern, wave front planarity, etc. Small defects, with the same order of magnitude of the interference pattern period, are more critical for the recording of diffractive components because their angular scattering spectrum convolutes with the diffractive spectrum of the grating\cite{3}, limiting the feasibility of holographic optical components.

Changes in the original photoresist thickness, or produced after development by variations of the light intensity produce changes in the line width of the lithographed structures (as shown in Figure 1(a)). Figure 2 illustrates the effect of the variations of the thickness of the photoresist structure in the line width of the masks. In this case, the noise in the line width
of the channels opened in the substrate depends also of the derivative of the profile as can be seen in the sections A and B in the Figure 2.

![Figure 2](image)

**Figure 2** – Scheme of the transferred noise from the mask to the substrate. The sections A and B where made at different derivatives A higher than B.

If \( z(x) \) is a function that describes the photoresist mask profile and \( \Delta z \) are the small changes on the photoresist thickness, the changes in the line width \( (\Delta x) \) may be represented by:

\[
\Delta x \approx \frac{1}{\partial z / \partial x} \Delta z
\]

where \( \partial z / \partial x \) is the derivative of the function \( z(x) \). In this way, the effect of a noise \( \Delta z \) will be reduced in the line width of the opened channels \( \Delta x \) by using high derivative mask profiles.

### 2. EFFECT OF THE DEVELOPMENT PROCESS

Although the holographic pattern is sinusoidal, the profile recorded in relief in the photoresist film depends on the development process. If the photoresist development rate is a linear function of the exposure light energy, the recorded profile will be also sinusoidal. This type of response is more suitable for the recording of holograms\(^4\) where several interference patterns are superimposed. For lithography, however, a high non-linear response is more desired. Using the non-linearity of the development process, it is possible to obtain a squared profile in the photoresist, in spite of the sinusoidal interference pattern\(^5\). Such profiles reduce the noise in the holographic photoresist masks because they present a higher derivative \( \partial z / \partial x \).

![Figure 3](image)

**Figure 3** – Response curve for the photoresist AZ 1400-17 in two types of developer diluted in DI water: AZ 400K (1:4) and (1:6); AZ 351 (1:3).
Thus, to control the recorded profile in the photoresist it is necessary to know the response of the photoresist in each developer as a function of the exposure energy. This curve brings information about the linearity of the development and depends of both photoresist and developer. The Figure 3 shows three of these curves for the AZ 1400-17 photoresist in two developers. Using these curves it is possible to know the necessary development time for each exposed energy and it is possible also to simulate the recorded profile that may be obtained using determined experimental conditions.

The results of two simulations using two of these curves are shown below in Figure 4. We can see that different profiles can be obtained by choosing appropriate conditions of energy and development.

![Figure 4](image_url)

**Figure 4** — Simulated profiles recorded in photoresist using the two different developers, changing the development time to obtain similar depths.

Figure 5 shows examples of gratings recorded in linear and non-linear conditions of development respectively.

![Figure 5](image_url)

**Figure 5** — SEM photographs gratings recorded in AZ 1400-17 using different development process. (a) developed in AZ 351 (1:3); and (b) in AZ400K (1:4).

The Figure 6 (a) shows SEM photographs of the cross section of masks recorded in AZ 1400-17 on substrates of InP, using linear and non linear processes respectively. Figure 6 (b) show the same samples in perspective. As it can be seen in this Figure 6, the square profiled masks present less noise than the sinusoidal masks. Besides the square profiled masks presents less noise in the lithography they have an additional advantage that are more tolerant for excess of development time.
3. PHASE PERTURBATIONS EFFECTS

The other main problem of holographic exposures is the low repeatability due to phase perturbations between the interference waves during the exposure. These perturbations are generated by thermal changes in the refractive index of the air in the arms of the interferometer or by mechanical vibrations of the components. The perturbations reduce the contrast of the fringes adding a light background and reducing the depth of the recorded mask. To increase the depth of the mask, it is necessary a longer development time. This fact allied with the isotropy of the wet development, produce a strong narrowing of the peaks of the structures that limits their maximum amplitude and may leads to the complete collapse of the structure. This effect is stronger in linear development conditions (high sensitivity). Even using non-linear development conditions (high contrast), in the presence of such perturbations it is not possible to record squared profiled masks. Figure 7 clearly demonstrates this fact. Both gratings are recorded in AZ 1400-17 and developed in AZ400K 1:4 (non-linear condition). The first sample (a) presented an exposure with thermal perturbations while the second (b) was stable.

Figure 7 – SEM photographs of holographic masks recorded in AZ 1400-17 with the same exposure energy (600mJ/cm²) developed in AZ400K 1:4. (a) with phase perturbations and (b) without phase perturbations.
This behavior can be seen also using a simulation whose results are shown in the Figure 8. For gratings with the same exposure energy and development time, the resulting amplitude for the grating with phase perturbation is lower. If the development time is increased in order to increase the grating amplitude the peaks are strongly narrowed.

![Figure 8 - Simulated profiles adding a light background of 50% of the total exposure energy.](image)

Even for the recording of masks with thin thickness, if the fringes of the interferometer are not stable it is not possible to obtain squared profiles. In this way the control of the phase perturbations is essential to for the recording of holographic masks.

In our case we use a fringe locked system that uses a residual real time grating that is formed in real time in the photoresist film. The system is very sensitive and allows the simultaneous stabilization and the monitoring of the recording. A scheme of the holographic setup with the fringe stabilization system is shown in Figure 9.

The system uses the wave mixing between the transmitted wave and the wave diffracted in residual grating that is being formed in real time. The system uses synchronous detection techniques. The reference signal as well as the correction signal is introduced in the system through a mirror supported by piezoelectric crystals in one of the arms of the interferometer. This signal produces a small lateral shift of the interference pattern with the same reference frequency. This displacement is converted by the wave mixing in a light intensity on the detector fixed in the direction of one of the beams transmitted through the grating.

![Figure 9 - Holographic exposure system with the fringe stabilization control.](image)

The detected signal has harmonics of the reference signal that can be measured using a lock in amplifier. The second harmonic signal is proportional to the phase perturbations of the interference pattern while the first harmonic is proportional to the diffraction efficiency of the grating. The second harmonic is amplified and added to the high voltage power supply of piezoelectric crystals to correct the slow phase perturbations. The first harmonic ($V_0$) evolution should follow a curve of the type.

\[
2^{18}
\]

\[
-0.3
\]

\[
-0.6
\]

\[
-0.9
\]

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\[ V_\Omega = A \left(1 - e^{-C(t-D)} \right) \]

where, \( V_\Omega \) is the first harmonic signal, \( t \) exposure time, and \( A, C, D \) constants related with system parameters and mechanism of grating formation.

The following of the evolution of the signal \( V_\Omega \) may be used to characterize the phase perturbations. Figure 10 shows examples of these evolutions.

Comparing the signal evolution of both samples we can observe that the sample A presents only rapid changes while sample B presents a higher average noise in the evolution. The resulting profiles of the corresponding recorded gratings are shown in Figure 11.

Although the gratings had been recorded in similar conditions, the results are very different. To investigate the causes of low repeatability of the recording, a study of the signal \( V_\Omega \) as a function of the reference frequency was made. This study showed that this signal presents several resonance frequencies in 3.5kHz, 4kHz and 5kHz. These resonances come probably from the piezoelectric atuador and can explain the instabilities presented in the recording of sample B. Both samples (A and B) were recorded using a reference signal \( \Omega = 2 \) kHz, so the second harmonic is switched at 4 kHz that is principal resonance of the system. Near the resonance the amplification is very high and feedback systems may became unstable.

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**Figure 10** — First harmonic signal evolution of two samples recorded using the same conditions but in different days \( f_{ref} = 2.0 \text{kHz} \), time constant = 300ms. (a) sample A (b) sample B.

**Figure 11** — Resulting profiles of gratings recorded in the samples (A) and (B) using the same exposure conditions in different days. The photoresist films where exposed in the interference pattern for an energy of 600mJ/cm², and developed in AZ400K 1:4. (a) during 40s (b) during 55s.
4. BEST RECORDED MASKS IN PHOTORESIST

In order to check this hypothesis some samples were recorded using another reference frequency fixed in 1.4kHz. The first sample was an AZ1518 photoresist film, exposed in the interference pattern with energy of 280mJ/cm² and developed in AZ351 (1:3) during 120 seconds (linear conditions). Figure 12 shows the $V_\Omega$ signal evolution and the corresponding grating profile. Note that the signal evolution presents a very low noise that is reflected in the high quality of the photoresist mask. Several samples were performed in similar conditions demonstrating that, by using these conditions, it is possible to record identical masks with good quality using holographic recording.

Another example of recording using the similar exposure conditions but using a photoresist film of AZ 1400-17, and developed in AZ400K (1:4) for 45s (corresponding to non linear conditions) is shown in Figure 13. As it can be seen, the association of a stable fringe pattern and non-linear development conditions allows the recording of masks with high quality and high aspect ratio (depth/period $\geq 1$ and depth/width $\geq 3$).

5. SELECTIVE DEPOSITION RESULTS

The possibility to record masks with high aspect ratio allows the use of a selective deposition technique similarly to Lift Off process used in lithography. In this process the photoresist mask is recorded direct into the substrate. After that a thin layer is deposited over the mask and the exposed areas onto the substrates. If the walls of the structure are vertical, depending on the
shadowing of the deposition process, there is no deposition on the walls, only in the bottom and the top of the structures. In this way the photoresist mask can be stripped remaining only the structure recorded on the deposited layer. An example of this process is shown in Figure 14.

![SEM photographs of the selective deposition process. (a) grating recorded in a photoresist film on a glass substrate, (b) the grating is covered by a-C:H film by PECVD (plasma enhanced chemical vapor deposition) (c) the structure recorded in the a-C:H film after the stripping of the photoresist.](image)

Figure 14 – SEM photographs of the selective deposition process. (a) grating recorded in a photoresist film on a glass substrate, (b) the grating is covered by a-C:H film by PECVD (plasma enhanced chemical vapor deposition) (c) the structure recorded in the a-C:H film after the stripping of the photoresist.

Figure 15 shows the resulting aluminum mask recorded on glass using the same technique. The aluminum film was deposited on the photoresist mask by thermal evaporation. Note that, for the recording of relief structures in metals this is a very interesting technique because it is very difficult to record photoresist holographic masks on high reflection films due to the high contrast standing waves.

![SEM photography of a structure recorded on an aluminum film on a glass substrate using the selective deposition technique.](image)

Figure 15 – SEM photography of a structure recorded on an aluminum film on a glass substrate using the selective deposition technique.

6. CONCLUSIONS

Our results demonstrate that two parameters are fundamental for noise reduction in the recording of holographic masks: the development conditions and the contrast of the interference pattern. In this way, to obtain good and reproducible photoresist masks in fundamental the control of the phase perturbations in the interference pattern. The use of non-linear development conditions reduces the noise of the recording structures and somewhat compensate the isotropy of the wet development allowing the recording of high aspect ration masks. Using deep photoresist masks it is possible to use selective deposition techniques for recording relief structures in thin films.

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8. REFERENCES