Optical microlithography on oblique and multiplane surfaces using diffractive phase masks

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Abstract. Micropatterning on oblique and multiplane surfaces remains a challenge in microelectronics, microelectromechanics, and photonics industries. We describe the use of numerically optimized diffractive phase masks to project microscale patterns onto photoresist-coated oblique and multiplane surfaces. Intriguingly, we were able to pattern a surface at 90 deg to the phase mask, which suggests the potential of our technique to pattern onto surfaces of extreme curvature. Further studies show that mask fabrication error of below 40-nm suffices to conserve pattern fidelity. A resolution of 3 μm and a depth-of-focus of 55 μm are essentially dictated by the design parameters, the mask generation tool, and the exposure system. The presented method can be readily extended for simple and inexpensive three-dimensional micropatterning. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction in any form or medium, except as authorized by copyright law, requires written permission. See https://spiedigitallibrary.org/terms-of-use

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1 Introduction
Microstructures on oblique and nonplanar surfaces enable unique functionalities in photonics,1,2 electronics,3 and microelectromechanics,4,5 and provide a broad array of interesting applications in high-gain antennas,6 radio-frequency identification devices,7 metamaterials,8 and transformation optics.9 For instance, combining diffractive microstructures atop a curved refractive surface can minimize aberrations in lenses, in a more compact way compared to the conventional methods by adaptive optics.10 In addition, micropatterning on the sidewalls of implantable neural probes could potentially lead to an effective approach of recording three-dimensional (3-D) neural signals.11,12 Meanwhile, shape modification in the vertical direction of microfluidic channels and 3-D integration may significantly enhance their performances.5,13

Optical projection lithography (OPL) on planar silicon substrates is the workhorse of the semiconductor industry due to its high throughput, resolution, and accuracy.14 In OPL, a photomask pattern is imaged with demagnification onto a planar photoresist layer that coats the silicon substrate. In general, it is difficult to utilize OPL to pattern nonplanar or oblique surfaces due to the limitations of the imaging optics. These limitations can be avoided by lens-less lithography that utilizes computer-generated holograms (CGHs) to directly project patterns onto the photoresist surface.15 Thus far, these approaches only project the pattern onto a single plane surface. In this paper, we extend this technique by designing diffractive optics that can manipulate the intensity of light in 3-D space, and thereby allow for patterning onto nonplanar and oblique surfaces. An alternative approach for lithography on nonplanar and oblique surfaces is to utilize a flexible template that contains a master pattern and apply this template conformally over the substrate. The pattern may be transferred via an imprint process16–18 or simply by exposure to ultra-violet (UV) light through the template.19 These approaches require contact with the substrate surface, which increases the potential for damage, increases defects, and reduces yield. Furthermore, these approaches perform well only for surfaces of small curvature since conformal contact is necessary. In contrast, our approach can be applied to surfaces of extreme curvature as illustrated by patterning of a substrate that is placed orthogonal to the diffractive mask.

2 Lithography Principle
Our approach is schematically explained in Fig. 1. A spatially collimated, temporally coherent uniform UV beam illuminates the mask [see Fig. 1(a)]. The sample to be exposed is placed at a specified distance behind the mask, where the light intensity distribution in three dimensions is controlled. The mask is designed using an enhanced direct-binary-search algorithm,20 where the optimization objective is to maximize intensity within prescribed patterns in multiple planes or within a 3-D volume. This numerical technique was successfully implemented in designing various diffractive-optical elements.21,22 In addition, the intensity uniformity within the target image has to be taken into account. Note that in optical lithography, the (positive-tone) photoresist serves as a nonlinear recording medium, where regions receiving energy higher than a threshold are selectively dissolved away in a developer. Hence, the mask only needs to ensure that the desired regions receive energy (which corresponds to light intensity multiplied by the exposure time) above a certain threshold (defined by the sensitivity of the photoresist at the exposure wavelength). The resulting mask comprised an array of discrete pixels, either in one dimension (along the X direction) or two dimensions (on the XY plane), where each pixel in the array applies a phase shift to the incident light. This resembles a traditional CGH, which is usually used to generate complex beams or images.23 The phase shift of each pixel is controlled during optimization. The array of optimal phase shifts is implemented as an array of pixels with varying...
hence, of each pixel in the array) was chosen so as to achieve
patterns at multiple planes (or in 3-D volume)
this corresponded to 430 nm.
index of 1.76 and illumination wavelength of 325 nm,
since the resolution of this process was limited to
three lines at

\[ \mu \cos \theta = 82 \mu \text{m} \]

linewidths of 30, 90, 180 μm and spacings of 60, 180, 120 μm are
were silicon wafers coated with a 1.3-μm-thick photoresist
mounted on a holder that was placed at 45 deg to the optical axis.
The illumination power density at the mask plane was 0.635 mW/cm²
and the exposure time was 90 s. The sample was developed in 352 developer
for 60 s. Optical micrographs of the patterns corresponding to
the regions close to the planes at z = 80, 81, and 82 mm [rectangular blocks of yellow-broken lines in Fig. 2(d)] are shown in Figs. 1(e)–1(g), respectively. Excellent agreement with the simulation results is seen. The linewidths at three z positions (80, 81, and 82 mm) are 34, 100, and 65 μm, respectively, which indicate the deviation of +4, +10, and +5 μm. These errors, together with the undesired exposures outside the designated line regions, are partially ascribed to overexposure. The simulated light intensity at three positions is plotted as blue lines beside the micrographs in Figs. 2(e)–2(g). By applying a proper threshold, it is possible to achieve clean lines with accurate widths and suppressed noises (black lines). Subsequently, numerical analysis will show how fabrication errors affect the exposure results. Additionally, a simulated 3 μm line [Fig. 2(h) representing the green box in Fig. 2(d)] was measured roughly 5 μm wide by exposure [Fig. 2(i) representing the green box in Fig. 2(e)].

In the next experiment, another mask was designed to project four letters “U,” “T,” “A,” and “H” onto X'Y' planes long (1000 pixels). Each pixel is quantized into 32 levels such that Δh = 13.9 nm. The 2-D target patterns are “U,” “T,” “A,” and “H” letters separated by a gap of Δd = 0.3 mm with an initial distance of \( d_0 = 5 \) mm [see Fig. 1(e)]. 18-μm wide lines are used to draw the patterns. Since they are periodic, each unit cell has dimension of \( L_x \times L_y = 180 \mu \text{m} \times 180 \mu \text{m} \) (60 × 60 pixels). The 2-D phase mask has square pixel with \( \Delta x = \Delta y = 3 \) μm and unit height of \( \Delta h = 6.8 \) nm (64 levels). Ridges in Fig. 1(c) and red parts in Fig. 1(e) stand for places to be exposed in positive-tone photoresist. Note that X’Y’ coordinates are employed in the mask space and the image space, respectively.

### 3 Exposure Results

In Fig. 2, the 1-D diffractive phase mask was designed to project three groups of lines of varying widths and spacings onto three planes positioned at \( z = 80, 81, \) and 82 mm, respectively. The target images are summarized in Fig. 1(c). Since these patterns have no variations in the Y direction, they could be exposed onto a plane tilted at 45 deg, instead of three exposures at three planes. In this way, it is also possible to record all the intensity patterns along the Z direction. The optimized phase mask topography is plotted in Fig. 2(b). Figure 2(c) shows an optical micrograph of the fabricated mask along with an atomic-force micrograph of the region delimited by the black rectangle. The multiple height levels and the discrete pixels are clearly visible. The simulated light intensity in the X’Z plane from \( z = 78.5 \) to \( z = 83.5 \) mm is shown in Fig. 2(d). At the design planes corresponding to \( z = 80, 81, \) and 82 mm, the patterns corresponding to 9 lines (period = 60 μm), 3 lines (period = 180 μm), and 5 lines (period = 120 μm), respectively, are clearly visible. The optical efficiency, \( \eta \) in one plane, is defined as the ratio of the energy within the desired pattern to the total energy incident on the mask. The calculated optical efficiencies are denoted in the figure. The samples for lithography were silicon wafers coated with a 1.3-μm-thick photoresist (Shipley 1813) and mounted on a holder that was placed at 45 deg to the optical axis. The illumination power density at the mask plane was 0.635 mW/cm² and the exposure time was 90 s. The sample was developed in 352 developer for 60 s. Optical micrographs of the patterns corresponding to the regions close to the planes at \( z = 80, 81, \) and 82 mm are 34, 100, and 65 μm, respectively, which indicate the deviation of +4, +10, and +5 μm. These errors, together with the undesired exposures outside the designated line regions, are partially ascribed to overexposure. The simulated light intensity at three positions is plotted as blue lines beside the micrographs in Figs. 2(e)–2(g). By applying a proper threshold, it is possible to achieve clean lines with accurate widths and suppressed noises (black lines). Subsequently, numerical analysis will show how fabrication errors affect the exposure results. Additionally, a simulated 3 μm line [Fig. 2(h) representing the green box in Fig. 2(d)] was measured roughly 5 μm wide by exposure [Fig. 2(i) representing the green box in Fig. 2(e)].
corresponding to $z = 5, 5.3, 5.6,$ and $5.9$ mm, respectively, as illustrated in Fig. 3(a). Figure 3(b) gives the topography of the designed mask. An optical micrograph of the fabricated mask along with an atomic-force micrograph of a small region is shown in Fig. 3(c). The multiple height levels of the square pixels are evident. Simulated light intensity distributions in the $X'Y'$ planes at the four planes are plotted in Figs. 3(d)–3(g). The corresponding optical efficiencies are also denoted in the figures. The measured optical intensity at the mask plane was $0.734$ mW/cm$^2$ and the sample was exposed for $52$ s. Optical micrographs of the corresponding exposed and developed patterns are shown in Figs. 3(h)–3(k). The experimental results agree very well with the simulation predictions. 21, 20, and 19 $\mu$m widths are obtained for the $18 \mu$m lines by measurements. Arrays of the patterned letters are given by microscope images in Figs. 3(l)–3(o). The noise present in the exposure results in Figs. 3(d)–3(g) are likely due to both overexposure and mask fabrication errors. Figures 3(p) and 3(q) show the exposure patterns predicted by implementing high (critical exposure) and low (overexposure) thresholds to the simulated light intensity distributions in Figs. 3(d)–3(g). Compared to Fig. 3(p), Fig. 3(q) clearly includes more noise and approaches the experimental results in Figs. 3(h)–3(k) with better accuracy.

In a third experiment, the sample substrate was placed orthogonal to the diffractive mask as illustrated in Fig. 4(a). For simplicity, the same phase mask as in Fig. 3 was used. The simulated light intensity distribution in the $X'Z$ plane is shown in Fig. 4(c) and the optical micrographs of the exposed and developed pattern is shown in Figs. 4(d) and 4(e). The pattern corresponds to the lower part of the four characters, i.e., the fat line at the bottom of “U” ($z = 5$ mm), the center line of “T” ($z = 5.3$ mm), the legs at

Fig. 2 Lithography on a 45-deg tilted surface. (a) Schematic of the exposure setup. (b) Height profile of the optimized 1-D phase mask. (c) Optical microscope image of one edge of the fabricated phase mask (inset: AFM measurement of a $50 \mu$m × $50 \mu$m region, and $\Delta x = 3 \mu$m pixel size is labeled). (d) Simulated intensity distribution in the $X'Z$ plane, where $Z$ is the direction of light propagation. Optical efficiencies at three planes are given. (e)–(g) Optical micrographs of the exposed and developed results at three regions enclosed by yellow blocks in (d). Measured linewidths at (e) $z = 80$, (f) $z = 81$ and (g) $z = 82$ mm are 34, 100, and $65 \mu$m, respectively. Blue lines are simulated intensity distributions at three planes and black lines represent the estimated exposure outcomes by applying a proper threshold to the simulated patterns. (h) and (i) Magnified views of small areas delimited by the green boxes in (d) and (e), respectively. The labeled $3 \mu$m line in (h) is experimentally measured $5 \mu$m.
the bottoms of “A” and “H” (z = 5.6 mm and z = 5.9 mm).

Fig. 3 Lithography on multiple planes parallel to the mask. (a) Schematic of the exposure setup. (b) Height profile of the optimized 2-D phase mask. (c) Optical microscope image of one corner of the fabricated periodic phase mask (inset: AFM measurement of a 50 µm x 50 µm region, and 3-µm pixel size is labeled). (d)–(g) Simulated intensity distributions of one period on the X’Y’ plane. Optical efficiencies are given. (h)–(k) Optical micrographs of the exposed and developed results of one period. Designed 18 µm lines have measured linewidths of 21, 20, and 19 µm, respectively. (l)–(o) Optical micrographs of the exposed and developed results of the periodic arrays. (d), (h) and (l) are letter “U” at z = 5.0 mm. (e), (i) and (m) are letter “T” at z = 5.3 mm. (f), (j) and (n) are letter “A” at z = 5.6 mm. (g), (k) and (o) are letter “H” at z = 5.9 mm. Estimated exposure results by applying high (p) and low (q) thresholds.

Fig. 4 Lithography on a surface orthogonal to the mask. (a) Schematic of the exposure setup. (b) Schematic illustrating that the exposure plane (pink) is the X’Z cross section of the intensity pattern of the phase mask that generates “U” “T” “A” “H” letters. (c) Simulated intensity distribution on the X’Z plane [pink surface in (b)]. Optical micrographs of the exposed and developed results of two (d) and four (e) periods. Simulated 81 and 30 µm lines in (c) have measured linewidths of 87 and 35 µm in (e), respectively.

the numerical results of an optimized 1-D phase mask that is designed to expose three narrow regions (~6 µm width) spaced by 0.3 and 0.9 mm in X’ and Z directions, respectively. It contains 1000 pixels of 3 µm width; the mask is 3 mm long. It has a maximum height of 600 nm and unit height of 10 nm (61 levels). The first exposure plane is 30 mm away from the mask [Fig. 5(a)]. The simulated
light intensity distribution shows highly efficient focus spots at the three designated positions in the $X_0Z$ plane [Fig. 5(c)]. By following the white dashed line in Fig. 5(c), light intensity received by the 71.6 deg tilted surface is plotted in Fig. 5(d). After applying a proper threshold (green line), the desired exposure pattern can be produced with excellent accuracy.

4 Discussion

4.1 Fabrication Error

Since the designed mask generates 3-D light field by introducing spatial phase modulation, it is necessary to pattern microstructures as close to the optimized height distribution as possible. Therefore, it is important to understand how fabrication errors of the diffractive phase mask affects its performance. Figure 6 plots the calculated optical efficiencies where Gaussian noise with zero mean ($\mu$) and various standard deviations ($\delta$) are added to the original design. The efficiencies are reduced with increased standard deviations. Both Figs. 6(a) and 6(b) indicate that errors with standard deviation greater than 100 nm ($\sim 23\%$ of the maximum height 430 nm) lead to meaningless results where noise overwhelms the signal. With $\delta = 40$ nm ($\sim 9\%$ of 430 nm), the 1-D and the 2-D masks have average optical efficiencies decreased from 70% and 60% to 54% and 45%. Insets of Fig. 6(b) include the intensity distribution simulations of the 2-D phase mask with applied errors ($\delta = 5, 40,$ and 100 nm).
100 nm). 5-nm error has trivial effect on the signal-to-noise ratio. However, with 40-nm error the patterns start to lose their accuracy. This also explains the undesired exposures observed in Figs. 2(e)–2(g) and Figs. 3(h)–3(k), which occurred outside the designated regions [defined in Figs. 1(c) and 1(e)]. Based upon measurements, the height error in our grayscale lithography is about 30 nm. Hence, it is critical to suppress fabrication errors, especially $\delta < 40$ nm, by accurate calibration, process parameter optimization, and better condition control.

### 4.2 Resolution

The spatial resolution by the proposed lithography technique is primarily defined by the fabrication resolution of the phase mask. In this paper, we exploited the Heidelberg microPG101 machine with 3-µm mode write-head for grayscale patterning $(\Delta x = \Delta y = 3$ µm). Theoretically, the attainable resolution by OPL is defined by $C.D. = k_i / \lambda NA$, in which $\lambda$ is the illumination wavelength, $NA$ is the numerical aperture of the projection lens, and $k_i$ is a system-related scale coefficient.\(^{31-33}\)

For a pixelated phase mask $NA \approx \lambda / 2\Delta x$. Usually, $k_i$ takes a value of 0.5, which results in a resolution $C.D. \approx \Delta x$. In Figs. 2(b) and 2(i), a simulated 3-µm line was measured 5 µm wide due to overexposure and the limited resolution of the optical microscope. Similarly, the other measured linewidths are within +15% of the nominal values. Therefore, by optimizing exposure condition and minimizing mask fabrication error, it is possible to approach the predicted resolution. Additionally, smaller features can be achieved once an advanced mask generation tool is utilized (down to <1 µm resolution).

### 4.3 Defocus

Depth-of-focus (DOF) is another issue considered in OPL systems. Generally, a projection lens has a DOF determined by $DOF = k_2 \lambda / NA^2 = 4k_2 \Delta x^2 / \lambda$, in which $k_2$ is another system-related factor.\(^{32,34}\)

Assuming $k_2 = 0.5$, $DOF = 55$ µm for a $\lambda = 325$ nm laser with $\Delta x = 3$ µm. Contrary to conventional 2-D lithography, a shorter DOF is desired in micropatterning on oblique and multiplayer surfaces, since more pattern changes are expected within a certain distance. This can be realized by reducing the pixel size of the phase mask and using a long-wavelength light source. The optical efficiencies at various defocus planes are plotted in Fig. 7. The efficiencies drop to 60% at ±500 and ±100 µm defocus for both 1-D [Fig. 7(a)] and 2-D [Fig. 7(b)] masks. At the −100 µm plane [top inset of Fig. 7(a)], the letters “U” and “T” have well-preserved patterns, while the other two exhibit obvious distortions. On the other hand, “A” and “H” look good, while the first two have worsened shapes at the +100 µm plane [bottom inset of Fig. 7(b)]. Thus, in exposure experiments, it is crucial to control the gap between the mask and the sample as close to the designed value as possible.

### 5 Conclusions

Managing light intensities in 3-D space using broadband diffractive optics allows for a new and efficient technique to pattern micro-structures on oblique and multiplayer surfaces. Clearly, this technique can be extended to conventional 3-D lithography. Compared to scanning two-photon lithographic techniques, the reported method is based on a single optical exposure and effectively avoids high-power pulsed lasers and slow scanning schemes.\(^{34,35}\) Our technique can be readily adapted for high-throughput manufacturing. The diffractive phase mask allows for a large number of degrees-of-freedom, which permits generation of complex geometries in 3-D space. The technique currently suffers from crosstalk between the patterns as is evident in Figs. 3(d)–3(g). This effect can be reduced by the use of smaller fabrication pixels, which will provide many more pixels, and hence more degrees-of-freedom for the optimization algorithm. Shrinking pixel size also helps in improving patterning resolution. Furthermore, our previous work in broadband diffractive optics\(^ {20}\) indicates that with a larger number of pixels, the sensitivity of the projected pattern to pixel errors is also minimized. One challenge in the reported method is that the resolution in the Z-axis is limited by the DOF of the diffractive-optical mask. Distances between the exposure planes that are several multiples of this DOF are necessary to effectively separate different patterns. The DOF can be decreased by using smaller pixels and longer wavelengths. In addition, the computer-generated micro-optic device can be faithfully replicated, and thus mass-produced via roll-to-roll nanoimprint.\(^ {18}\) The next step is to explore its vast capabilities in 3-D micropatterning.
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