

# Photolithographic patterning of bihelical tracks onto conical substrates

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**Abstract.** We demonstrate the direct photolithographic patterning of a grossly nonplanar substrate by creating 62- $\mu\text{m}$  helical tracks on a 22-mm-high cone. The projection of focused light onto the 3-D surface is achieved using a computer-generated hologram (CGH) suitably illuminated so as to create the required pattern on the photoresist-coated surface. The approach adopted forms the basis of a novel method for patterning nonplanar structures. We address the key challenges encountered for the implementation of holographic photolithography in three dimensions, including mask design and manufacture, exposure compensation, mask alignment, and chemical processing. Control of linewidth and resolution over the nonplanar surface is critical. We describe the methods adopted and critically assess the structures created by this process. The bihelical cone is representative of a broadband, high-frequency coil-like structure, known in wireless communications as a log-periodic antenna. © 2007 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2824377]

Subject terms: holography; lithography; log-periodic antennas.

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## 1 Introduction

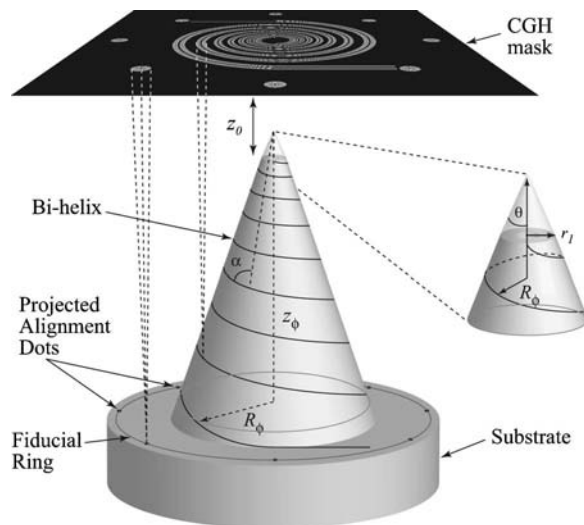
Photolithography is traditionally confined by the paradigm of transferring a pattern from a flat mask onto a flat substrate. The transferred pattern is subject to undesirable diffraction effects unless mask/substrate flatness and alignment precision are tightly controlled. In extending photolithography to the patterning of nonplanar substrates, the minimum feature size is limited by diffractive line broadening; for example, the minimum pitch for line tracks traversing a 54-deg sloping sidewall of an anisotropically etched 350- $\mu\text{m}$ -thick silicon wafer is limited<sup>1</sup> by conventional photomask imaging to around 40  $\mu\text{m}$ .

The photolithographic process can be made more robust to variations in substrate height by compensating for diffractive line broadening in the mask pattern, i.e., reducing the mask line-width in step with mask-substrate separation. This approach has been demonstrated by patterning 140- $\mu\text{m}$ -pitch electrical connections over a 500- $\mu\text{m}$ -high piezoelectric print head actuator<sup>2</sup> but is limited to small variations in substrate height due to degradation of the sidewall slope of the developed photoresist.

Diffraction is employed advantageously in the patterning of planar substrates by the use of model-based optical proximity correction (OPC) techniques in which the mask pattern is predistorted such that the projected image more closely matches the desired shapes.<sup>3</sup> A similar approach can be used for 3-D photolithography, as has been used for imaging a line on a sloping surface.<sup>4</sup> In this instance the mask constitutes a computer-generated hologram (CGH).

The structure considered here is a bihelix consisting of a

pair of nonplanar curves following a conical substrate (Fig. 1). This geometry has potential for use in ultrawideband antennas or inductors. Patterning methods adopted hitherto for these grossly nonplanar substrates are based on rotation of the substrate during direct laser patterning<sup>5</sup> or by wrapping flexible circuit boards around a mandrel.<sup>6</sup> Provided the depth of field can be sufficiently extended, photolithography is potentially superior to these sequential or direct



**Fig. 1** Nonplanar photolithography system:  $\theta=16.5$  deg is the cone half-angle,  $z_0=8.4$  mm is the exposure offset,  $r_1=1$  mm is the initial helix radius, and  $\alpha=74.2$  deg is the wrap angle of the helix.

write processes for large-volume manufacture. We envisage that this nonplanar photolithography method will enable many novel patterning strategies.

## 2 Mask Computation

The CGH mask is the key component of the system because it defines the projected 3-D light distribution by modulating the incident wavefront. Since our current interest lies in nonplanar surfaces, an efficient method for finding a suitable CGH mask is to restrict calculation to only the surface of interest. Simplification of the problem is possible by decomposing the object into line segments and superimposing individual CGHs representing each line. The CGH for each line takes the mathematical form  $H(x, y) = \exp(i\pi y^2/\lambda z)$ , where  $(x, y)$  are the coordinates in the hologram plane,  $\lambda$  is the exposure wavelength, and  $z$  is the distance between the hologram and the object.<sup>7</sup>

Our strategy is based on direct modulation of the line CGH equation, although more complex generalized schemes have been reported for achieving generalized focal curves.<sup>8</sup> The device's bihelical geometry is described by two parameters,  $z_\phi$ , the angle-dependent distance between the hologram and the focal plane, and  $R_\phi$ , the radial location of the line:

$$R_\phi = r_1 \exp(a\phi) \quad z_\phi = z_0 + \frac{R_\phi}{\tan \theta} \quad (1)$$

where  $a = \sin \theta / \tan \alpha$  (see Fig. 1).

For each helical line of the bihelix device, a quantized CGH distribution  $H(r, \phi)$  is computed in polar coordinates:

$$H(r, \phi) = \begin{cases} \exp\left[i\frac{\pi}{\lambda z_\phi}(r - R_\phi)^2\right] & \text{if } |r - R_\phi| \leq \frac{L}{2}, \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where the second line of the bihelix is obtained by a rotation of 180-deg about the  $z$  axis. The localized width of the modulated region is limited according to parameter  $L$  such that aliasing of the mask pattern does not occur for the chosen pixel size  $p$ . The required limiting function is determined by examining the local spatial frequency in Eq. (2):

$$L = \beta \frac{\lambda z}{p} \quad (0 \leq \beta \leq 1), \quad (3)$$

where  $\beta$  can be used to restrict the CGH width to a fraction of the alias limit. This approach is particularly suited to many device-level applications, where the following can be assumed:  $H(r, \phi)$  has a smoothly varying depth function ( $z_\phi$ ), the resist thickness compared to linewidth effects is small, and surface reflections do not strike the substrate.

It can be shown using the stationary phase method that the reconstructed image is a good approximation to the desired curve,<sup>8</sup> whereby small segments of the curve are reproduced by converging cylindrical wavefronts. These meso-optical diffractive elements utilize zero-order light in the reconstructed lines, hence keeping the light intensity high and minimizing the exposure time. The strategy for nonplanar lithography is to arrange for each line CGH to

follow the surface of the substrate. Simple circuit geometries are thus encoded in the exposure mask, complete with depth information.

At its simplest, the mask is realized as a binary amplitude pattern ( $[0, 1]$  e.g., chrome-on-glass). A binary phase pattern ( $[0, \pi]$ , e.g., etched glass) offers a factor of 4 increase in peak intensity. Yet more advanced representations can be used to improve the line profile and may involve multilevel phase and amplitude. The CGH mask configuration adopted here comprises an array of pixels ( $p = 10 \mu\text{m}$ ) encoded by a combination of two-level phase and amplitude blocking. Blocking is used in regions that lie outwith the localized radial width  $L$  [Eq. 2]. Due to the tight radius of curvature toward the tip of the cone, overlapping can occur in the CGH pattern between successive turns of the helix, leading to nulls in the intensity pattern when binary representations are used. Within the constraint of a binary phase CGH configuration, the localized radial width was restricted by setting  $\beta = 0.75$ .

For a small section of the reconstructed helical track, the cross-sectional intensity profile can be approximated by a  $\text{sinc}^2$  function.<sup>4</sup> The full width at half height  $W$  of this function on the sloping surface is approximated by

$$W \cong \frac{\lambda z}{L \sin \theta}. \quad (4)$$

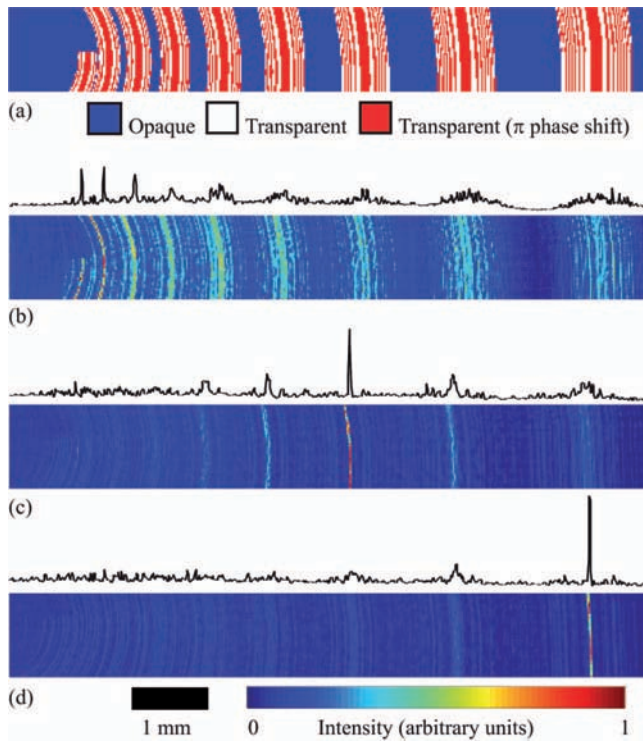
If the CGH segment width  $L$  is restricted according to Eq. (3), then Eq. (4) becomes independent of  $z$  and fixed for a constant value of  $\beta$ .

The magnitude of the  $\text{sinc}^2$  function is, however, dependent on  $z$ , hence the width of the actual line imaged into photoresist will vary with  $z$ . We previously described enhancements to our CGHs in which control of the linewidth and termination on planar substrates can be enhanced.<sup>9</sup> It is anticipated that similar enhancements can be achieved for tracks on nonplanar substrates, possibly by the use of 3-D direct transforms or iterative methods.<sup>10,11</sup>

## 3 Demonstration

The expanded beam from a spatially filtered diode laser (403 nm, 50 mW) was collimated to provide a beam of diameter 2.5 cm with less than 5% intensity variation. The extent of the uniform beam region could be increased by using, for example, refractive beam shaping,<sup>12</sup> however for simplicity, the central portion of the expanded Gaussian beam was used here. Speckle effects were not a significant issue in this configuration.

Binary phase shift masks (PSMs) are used in submicrometer lithography to enhance the patterning of dense structures.<sup>3</sup> Our binary phase CGH could be manufactured in the same way, by etching of a glass mask blank, but for practical reasons, we chose instead to create the necessary phase shifts by selective removal of a transparent layer deposited on top of the photomask substrate. A standard chrome on glass mask blank was first patterned with the amplitude blocking layer. A 400-nm layer of polymethylmethacrylate (PMMA) with a refractive index  $n = 1.5$  was then spin coated on top of the patterned mask blank. The

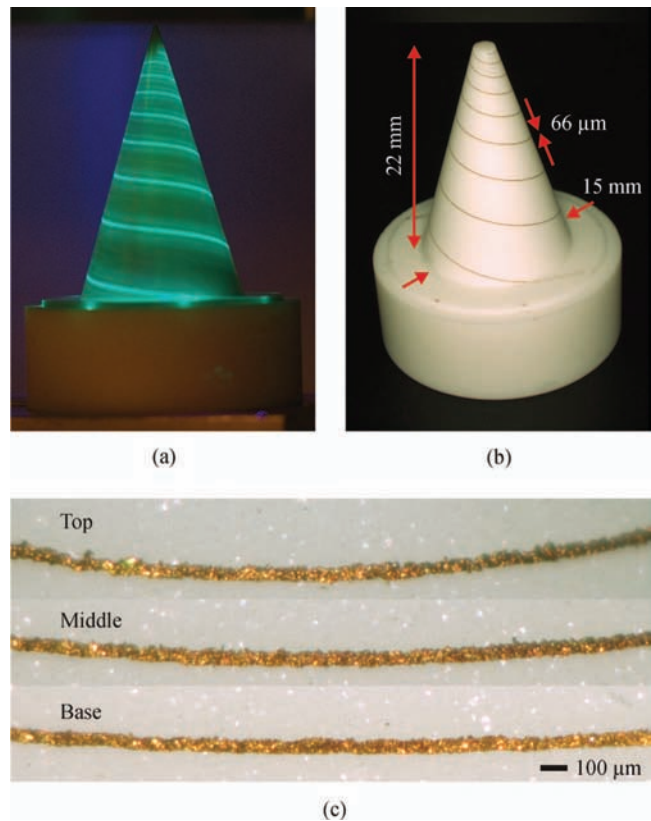


**Fig. 2** Bi-helical CGH and resulting images: (a) schematic representation of a portion of the binary phase CGH for projecting a double helix onto a cone; (b) to (d) false color CCD images and intensity cross sections obtained at CGH-CCD separations corresponding to (b) top ( $z=10$  mm), (c) middle ( $z=21$  mm), and (d) base ( $z=32$  mm) of the cone. We can see that the turns of the helix are formed at the prescribed separations.

PMMA layer was then etched in an oxygen plasma, using a thick patterned photoresist as the etch mask, to generate the required  $\pi$  rad phase shift layer [Fig. 2(a)].

The photoresist-coated substrate must be aligned to the mask with respect to all six degrees of freedom for 3-D lithography. Coarse  $z$  alignment can be achieved using a mechanical spacer. For a fine alignment, zone plates are employed around the periphery of the mask (see Fig. 1) to project light spots that can be made to coincide with fiducial marks on the substrate. In a basic realization, the same light source is used for exposure and alignment with a shutter shielding the active substrate. Alternatively, a second light source with a wavelength to which the photoresist is not sensitive can be used for alignment, provided an appropriate zone plate scale change is made.

A prerequisite for chemically processing the substrates is the uniform deposition of a photoresist layer. Common methods such as spin coating and lamination result in non-uniform films and voids when applied to nonplanar surfaces. Effective spray coating of the photoresist can be achieved over moderate topographies of a few hundred micrometers, but for grossly nonplanar surfaces a better method is to use an electrodepositable photoresist<sup>2</sup> (EDPR). Here we applied a 5- $\mu\text{m}$  layer of positive acting EDPR (Rohm and Haas PEPR2400) to a glass-ceramic cone pre-coated with a 1- $\mu\text{m}$  electroless nickel seed layer. Following exposure and development of the EDPR, a buildup process was used in which 2- $\mu\text{m}$  gold was electroplated into the



**Fig. 3** Holographic imaging of bihelical pattern onto conical substrate: (a) test substrate during exposure, (b) substrate patterned with bihelical tracks; and (c) close-ups of gold tracks at top ( $w=55$   $\mu\text{m}$ ,  $\sigma=9$   $\mu\text{m}$ ), middle ( $w=66$   $\mu\text{m}$ ,  $\sigma=6$   $\mu\text{m}$ ), and base ( $w=64$   $\mu\text{m}$ ,  $\sigma=9$   $\mu\text{m}$ ) of the substrate ( $w$  is mean measured line width and  $\sigma$  is sample standard deviation).

developed pattern. The EDPR and nickel seed layer were then stripped to leave the required track geometry.

## 4 Results

Using the methods already described, the imaging of bihelical curves onto the cone was performed [Fig. 3(a)]. Subsequent processing resulted in tracks over the entire 22-mm height of the substrate [Figs. 3(b) and 3(c)]. Despite a nearly twofold intensity variation between the top and the base of the cone [Figs. 2(b) and 2(d)] and a rough substrate surface ( $R_a=2$   $\mu\text{m}$ ), it was possible to determine photoresist exposure and processing conditions that enable the full spiral to be imaged. The mean linewidth was 62  $\mu\text{m}$  (10 sample points each at the top, middle, and base of cone, standard deviation=9  $\mu\text{m}$ ). This is larger than the value of 42  $\mu\text{m}$  predicted by Eqs. (3) and (4) because in this instance, the photoresist exposure threshold corresponded to a value less than the half height of the sinc<sup>2</sup> intensity distribution. As with normal photolithography, the minimum line width for 3-D photolithography is dependent on the mask resolution and illumination wavelength.

The results presented here are far beyond the normal capabilities of photolithography and we foresee many applications for this novel nonplanar patterning technique in the fields of microelectromechanical systems (MEMS) and electronics packaging.

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