Nonplanar photolithography with computer-generated holograms

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We outline a method for accomplishing photolithography on grossly nonplanar substrates. First we compute an approximation of the diffraction pattern that will produce the desired light-intensity distribution on the substrate to be patterned. This pattern is then digitized and converted into a format suitable for manufacture by a direct-write method. The resultant computer-generated hologram mask is then used in a custom alignment tool to expose the photoresist-coated substrate. The technique has many potential applications in the packaging of microelectronics and microelectromechanical systems. © 2005 Optical Society of America

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Photolithography is generally performed on a nominally flat substrate, such as a silicon wafer or a printed circuit board. The growth of microelectromechanical systems and the search for higher-density electronics packaging solutions has led, however, to the requirement to pattern fine features onto nonplanar substrates. These substrates cannot be placed in close proximity to the (planar) masks. As a result, diffraction occurs between the mask and the substrate, causing distortions to the shapes of the required features.

A number of resolution enhancement techniques exist that can be used to compensate for such distortions, but these have been developed primarily for use with planar substrates.[1] These techniques were recently used to enhance the patterning of nonplanar substrates, for example, to facilitate the photolithographic patterning of 100-μm-pitch features over 500-μm-high steps.[2] An extension of this approach leads to the concept of holographic photolithography, a technique that was developed by Holtronic SA. The Holtronic approach is to generate a total-internal-reflection holographic mask from a real master, which permits the high-yield patterning of submicrometer features onto large flat-panel displays.[3] In this Letter we present a method for making masks composed of computer-generated holographic (CGH) patterns, which replace the master holograms.[4] We then examine the use of the CGH masks to pattern grossly nonplanar substrates.

The diffraction pattern in the CGH plane (X,Y) that results from a line in space characterized as shown in Fig. 1 is given in Ref. 5 as

$$H(X,Y) = \exp\left(j\frac{\pi}{\lambda z_x}y^2\right), \tag{1}$$

where λ is the wavelength of the light source and $z_x = z_0 - x\tan(\gamma)$, where γ is the angle between the line segment and the plane of the CGH. Translation of the line segment in the x and y directions can be accomplished by the introduction of a linear phase factor, while the orientation of the line with respect to the CGH axes (X,Y) is accounted for by a coordinate transform:

$$x = X\cos(\alpha) - Y\sin(\alpha), \quad y = X\sin(\alpha) + Y\cos(\alpha). \tag{2}$$

One can control the length of a line segment by truncating Eq. (1) in the x direction, in which case the resultant distribution in the image plane when $\gamma = 0$ is given by

$$|U(u,v)| = |f(u)|a\sqrt{\lambda z}\,\mathrm{sinc}(av/\lambda z), \tag{3}$$

where $f(u)$ is the complex Fresnel integral, z is the separation of the mask and the image plane, and a is the extent of the CGH in the y direction. It can be shown experimentally that this result also applies approximately to lines when $\gamma \leqslant 80°$.

The intensity of the line segment therefore varies as sinc^2 in the v direction, and in the u direction it may be approximated by a rect function:

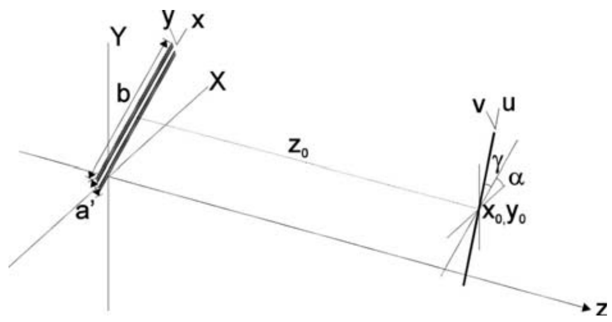

Fig. 1. Line geometry.

$$f(u) \cong \begin{cases} 1 & |u| \leq b/2 \\ 0 & |u| > b/2 \end{cases}, \tag{4}$$

where b is the extent of the line-segment representation in the x direction of the CGH. Superposition of several diffraction patterns defined in this way can be used to produce a CGH that forms an image composed of line segments. However, use of a CGH of this type as a lithographic mask is limited by the extremely high resolution required for imaging a fine line segment at a small distance from the mask, because the high-frequency fringes that are present at the extremities of the line-segment representation must be sampled without aliasing. We propose a modified version of Eq. (1) in which the diffraction pattern generated by each line segment is limited in both the x and the y directions to a finite area of the mask. The offset of a reconstructed line segment is achieved by an appropriate translation of this localized diffraction pattern:

$$H(X,Y) = \exp\left[j\frac{\pi}{\lambda z_x}(y-y_0)^2\right]\mathrm{rect}\left(\frac{x-x_0}{b},\frac{y-y_0}{a'}\right), \tag{5}$$

where a' is the localized limit of the line-segment representation in the y direction of the CGH and x_0 and y_0 are the offsets of the line from the optical axis in the x and y directions, respectively. This distribution reduces resolution requirements in the CGH.

For the CGH to be written by use of a conventional plotting device it is necessary for a sampled version of the distribution in Eq. (5) to be converted to a binary format; this can be achieved in a number of ways.[6,7] For the example described in this Letter, a simple thresholding method was used in which the real part of Eq. (5) was sampled on a pixel grid and those pixels with a positive value were set to 1 (transparent) whereas all others were set to 0 (opaque).

One can find the image that results from a line-segment CGH of this type by expressing the binary pattern as a Fourier series and summing the images formed by each of the Fourier components. In this way, a good approximation to the resultant line-segment amplitude in the v direction after insignificant terms are dropped and with small phase variations neglected is

$$|U(v)| \approx \frac{a'}{\pi}\,\mathrm{sinc}\left(\frac{a'v}{\lambda z}\right) + \frac{\sqrt{\lambda z}}{2}\,\mathrm{rect}\left(\frac{v}{a'}\right) + \frac{\sqrt{\lambda z}}{\pi}\,\mathrm{rect}\left(\frac{v}{2a'}\right). \tag{6}$$

A three-segment line CGH produced with this approximation is shown in Fig. 2; Fig. 3 shows the approximate and measured intensity distributions produced at the focal distance of a line segment. The distribution can be seen to consist of the required sinc^2 profile, combined with a broad spread of background noise. Constructing the CGH as a binary phase mask would eliminate the second term in relation (6) and improve the signal-to-noise ratio.

Fig. 2. Thresholded CGH representation of a stepped line segment.

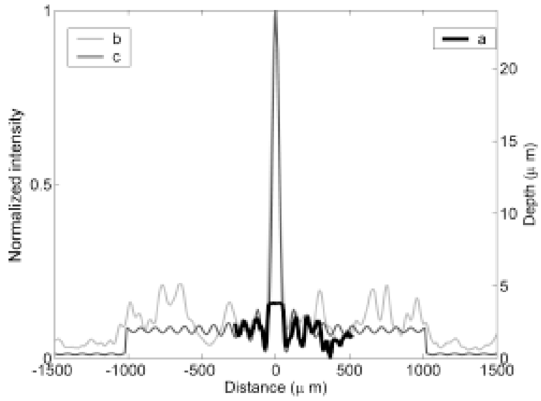

Fig. 3. Comparison of the approximation in relation (6) with CCD and depth profile data: (a) diamond stylus depth profile data (photoresist approximately 3 μm thick), (b) CCD data, (c) cross-sectional approximation.

In a conventional CGH, the multiple images that result from sampling must be spatially separated if the primary image is not to be distorted, leading to the requirement for a minimum mask–substrate separation for a given mask resolution. However, in the case of a CGH composed of line-segment diffraction patterns as in Eq. (5) and represented by a binary amplitude distribution, these aliasing constraints can be relaxed because there are no multiple images formed by the line segments in either the u direction, in which the CGH representation is simply a series of long rectangular apertures, or the v direction, where the image plane amplitude distribution is as outlined above. Parallel line segments can therefore be imaged at a relatively fine pitch, provided that the background noise components that are present in relation (6) are taken into account. If the extent of each line-diffraction pattern in the y direction is taken as being the largest possible for the given pixel spacing, such that aliasing does not occur, then it can be shown that the full width at half-height of the sinc^2 line profile becomes approximately equal to the pixel spacing in the mask, regardless of mask–substrate separation z.

For grossly nonplanar surfaces, application of a uniform layer of photoresist can be problematic. Spray nozzles have been developed that allow modest topographies to be covered uniformly, but for complex substrate shapes the preferred method is to use an electrodepositable photoresist[8]; in our experiments we used a positive-acting electrodepositable photoresist (PEPR 2400). With careful control of the photoresist's composition[9] a bias voltage of 175 V at room temperature results in a uniform 3-μm-thick layer over the entire substrate. A custom-built alignment tool was used to expose the photoresist-coated substrate through the CGH mask. The light source was the beam-expanded spot from a Coherent I304 Ar-ion laser, producing 100 mW of TEM_{00} power at 355 nm.

Using the approach detailed above, we wrote a 40-μm-resolution CGH mask (Fig. 2) consisting of three line segments that recreates a line tracing a path over a 4-cm step at 10 cm from the mask. A stylus depth profiler was used to record a depth profile across the imaged line segment, and further data were captured from a CCD camera. These results are compared with the approximation in relation (6) in Fig. 3. Accurate control of exposure and developing conditions has enabled us to image a reasonably consistent 100-μm-wide line along the length of the substrate (Fig. 4).

In conclusion, we have shown that computer-generated holographic masks consisting of thresholded line segments can be used to pattern lines onto a grossly nonplanar substrate. We have also shown that the linewidth can be controlled over these surfaces and that the minimum feature size is approximately equal to the resolution of the computer-generated mask, regardless of substrate–mask separation.

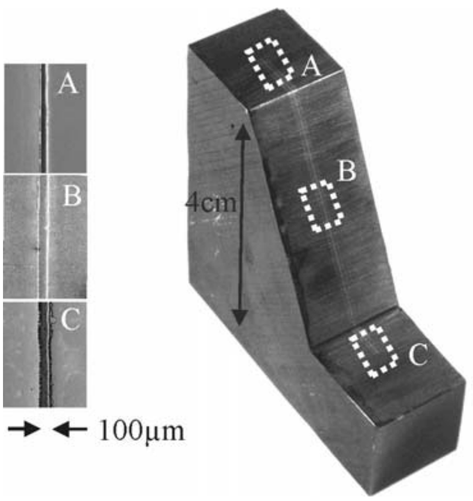

Fig. 4. Images of line–slope–line patterned substrates. Right, photograph of an imaged line in a photoresist-coated substrate (brass block); left, scanning electron microscope images of nickel tracks deposited onto the line (Ti–Au-coated Si substrates).

Representations of the CGH other than the simple binary format used here are currently being investigated, together with modified versions of the distribution in Eq. (5) that will permit better control of the width and length of line segments. Masks consisting of several parallel line segments are being tested to determine the resolution limits imposed on these patterns by the background noise, and the effect on the exposed photoresist of intersecting lines is also being considered.

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