Photolithography on Three Dimensional Substrates

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Abstract

Photolithography is the primary technique for patterning planar substrates. However, some higher-density packaging solutions require fine features to be patterned onto grossly non-planar substrates, for example, in mechanical, optical and fluidic microsystems and in novel packaging schemes. Standard photolithography cannot be used in these cases because the inevitable gap between the (planar) mask and (non-planar) substrate causes diffractive line broadening and loss of resolution. We address this issue by realising the mask as a Computer Generated Hologram (CGH), which can then be illuminated to generate an image in space corresponding to the required non-planar profile. The CGHs are derived from analytical expressions and encode both amplitude and phase information. We illustrate the performance with a 100µm line exposed onto a substrate in the form of a plane/slope/plane, in which the change in depth is 40mm. Enhancements to the line shape are discussed that make the technique more robust to manufacturing process variations. The fact that features in the range 10-100µm can be imaged at large distance whilst coping with significant changes of depth indicates that the technique shows great potential in the microelectronics packaging industry.

Introduction

Photolithography is the primary technique for pattern transfer within the microelectronics and printed circuit board (PCB) industries. The continual push to keep pace with Moore's Law [1] means that it is the subject of intense research. Projection optics used in sub-micron resolution lithography tools has a very narrow depth of field and so it is vital to position the substrate at the correct separation from the reduction lenses. The same constraint applies to the contact and proximity exposure tools favoured by PCB manufacturers. Incorrect mask-substrate separation causes diffractive line broadening and loss of resolution. This precludes the use of photolithography in writing fine-pitch patterns onto non-planar substrates, such as micro-sensors, micro-optical and micro-fluidic components, since it becomes difficult to obtain an in-focus image over the entire 3D topography. An alternative technique for these cases is to use a direct-write tool, typically a laser, however this can be unattractive due to the lower throughput and extra capital costs [2].

Resolution enhancement techniques (RET) are being developed for sub-micron lithography [3] and these suggest some ways in which a mask pattern can be modified to enable high resolution to be maintained over a grossly non-planar surface. The simplest enhancement is to modify the feature dimensions on the mask to compensate for the diffractive line broadening. For instance, the projection of a 100µm line onto the side wall of an anisotropically etched silicon wafer would require a tapering mask feature that started with a width of 100µm and narrowed to (say) 90µm as the mask-substrate separation increased. The exact amount of narrowing would depend on the optical arrangement and the processing conditions for the photoresist. This technique has been shown to be successful for 140µm pitch connections over a 500µm step on the actuators of inkjet print heads [2], but does not cope with more extreme situations. Christensen *et al* [4] achieved a minimum line pitch of 60µm for a similar geometry.

The basis of the work presented in this paper can be considered as a substantial enhancement to another RET technique, namely the addition of sub-resolution assist features around mask shapes. Assist features are effective because the light striking the mask has a degree of partial coherence making it possible to generate constructive and/or destructive interference at the substrate surface and so modify the projected line shapes. The extension of this idea to the patterning of grossly non-planar substrates requires constructing the mask as something closer to a full hologram, so that, when illuminated with a sufficiently coherent light source, the required non-planar light distribution is produced [5, 6].

Computer generated holograms

The traditional method of forming a hologram, recording the interference between a reference laser beam and an object beam on a light sensitive plate, requires a pre-existing master substrate that is already patterned with the required features. This is the basis of a successful technique for the robust patterning of sub-micron features onto large flat panel displays that has been developed and commercialised by Holtronic [7]. However, the production of the master substrate is expensive and, for 3D geometries, can be very difficult. The alternative is to compute the required hologram for a given pattern and then use a standard mask writing tool to write the mask. This produces a computer-generated hologram (CGH). This is the basis for an x-ray projection lithography technique [8] in which the CGH is calculated using an iterative search method similar to that developed by Gerchberg-Saxton [9]. Unfortunately, this method cannot readily be extended to complicated non-planar topologies and, therefore, an alternative approach to the generation of the CGH is required. The patterns required for photolithography are generally composed of lines, rectangles and circles. These are simple shapes and it thus becomes possible to employ analytical methods to determine the required CGH patterns. Frère *et al* [10] have demonstrated a technique for determining analytically the CGH for line segments on flat and tilted surfaces and this has been extended to include curved surfaces [11]. These analytical methods are computationally less expensive than the iterative search methods.

The iterative and analytical CGH methods generate complex functions that encode both the amplitude and the phase of the light emanating from each point on the mask. It is not possible to print these complex numbers directly, so quantisation of the functions is required first. The simplest quantisation scheme is to ignore the phase component and binarise the amplitude component into either black (opaque) or white (clear). The resulting binary amplitude CGH can then be produced using a standard chrome on glass mask blank. Alternatively, the phase components can be quantised and then realised by selective etching into a glass mask blank, a technique that is already used for the production of phase shift masks (PSM). The functions must also be pixelated, with the minimum pixel size being governed by the mask writing tool. Quantisation and pixelation both cause a degradation of the quality of the image projected by the CGH. This may not be an important issue for certain applications of CGHs, such as 3D-visualisation [10], however, the noise introduced by these processes has presented a large hurdle to the use of CGHs for photolithography.

Photoresist deposition

A second aspect to photolithography in three dimensions is the deposition and subsequent processing of a controlled-thickness photosensitive layer on the substrate surface. The standard microelectronics photoresist deposition technique entails spinning a liquid precursor on to a wafer, whilst in the PCB industry dry-film resists are commonly used. Neither of these methods is suitable for substrates that are not flat. Other techniques that do offer some planarising potential include dipping and spraying, but the best candidate appears to be the use of electro-depositable photoresist (EDPR). These products have been developed as a replacement to dry film resists [12], but have also found many applications within the MEMS domain (e.g. [13]). The EDPRs are deposited by means of a simple DC electroplating process, thus they require that the substrate has a conductive seed layer, which can easily be deposited by electroless plating. The growing photoresist film acts as an insulator, causing the deposition to be self-limiting and resulting in a uniform thickness layer over the entire substrate, regardless of its shape. In these studies, we have used Eagle 2100, a negative acting EDPR supplied by Rohm and Haas Electronic Materials. A deposition voltage of 150V produces a 5μm thick photoresist layer.

Mask aligner

The optical arrangement used to project the CGH is similar to that for a standard soft-UV mask aligner, but with a laser replacing the mercury arc lamp (Figure 1). This modification is necessary because we require a more spatially coherent light source with which to illuminate our CGHs. We recognise, however that the suitably collimated beam from a UV arc lamp beam may be sufficiently coherent for some applications. For our studies, we have used a Coherent 'Cube' diode laser producing 50mW at 403nm. The emission is not strictly UV, but it does have a sufficiently short wavelength to expose the photoresist. A spatial filter/beam expander assembly produces a TEM00 mode beam that impinges on the CGH. We are investigating the incorporation of a refractive beam re-shaper into the optical train to smooth the intensity distribution across the beam whilst maintaining a constant phase profile. The substrate is positioned on an x, y, z, θ alignment stage.

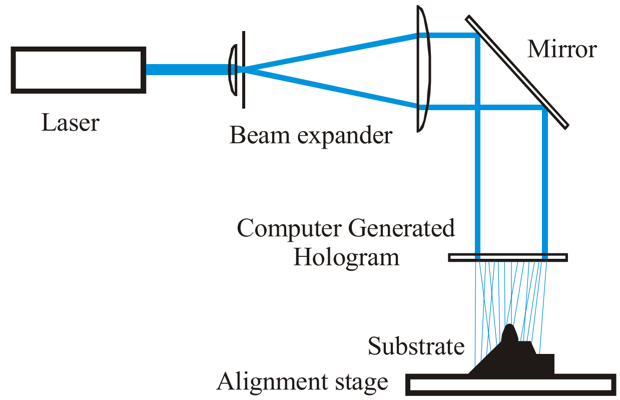


Figure 1 Optical arrangement for CGH projection

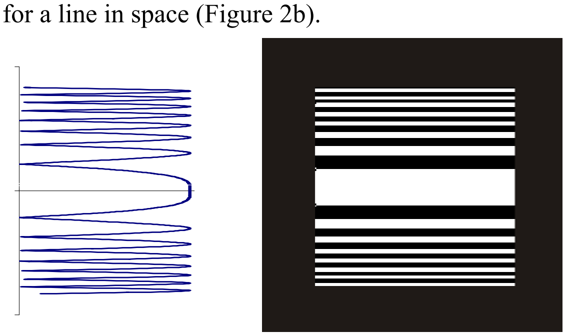
The same (attenuated) light source is used during the mask-substrate alignment. A special test substrate/CGH combination is used first to ensure that the beam propagation direction is perpendicular to the CGH. The required CGH and substrate are then installed. Mask–substrate alignment is achieved using the projection of special zone plates on to the edges of the substrate e.g. [14]. During this step, the central portion of the mask is obscured using a shutter. The alignment marks allow x, y and θ alignment, as in a normal alignment tool, but uniquely they also permit z alignment, since they only produce a definite spot at a particular separation z from the mask.

Basic CGH

The analytical equation for the hologram pattern that generates a line in space along the x-axis at distance z from the mask is that of a cylindrical wave and is given by [10]:

$$H(x,y) = \exp\left(j \frac{\pi}{\lambda z} y^2 \right) \qquad (1)$$

Here, λ is the wavelength of the illuminating radiation. The real part of (1) is a *chirp* function along the y-axis (Figure 2a). If we binarise the *chirp* function and truncate it in the x and y directions with a *rect* function we obtain the binary amplitude CGH for a line in space (Figure 2b).



(a) (b)

Figure 2 (a) The real part of *H* and (b) the resulting binary amplitude CGH for a line in space

The resulting image, formed at the focal length z when projecting this CGH, is shown in Figure 3.

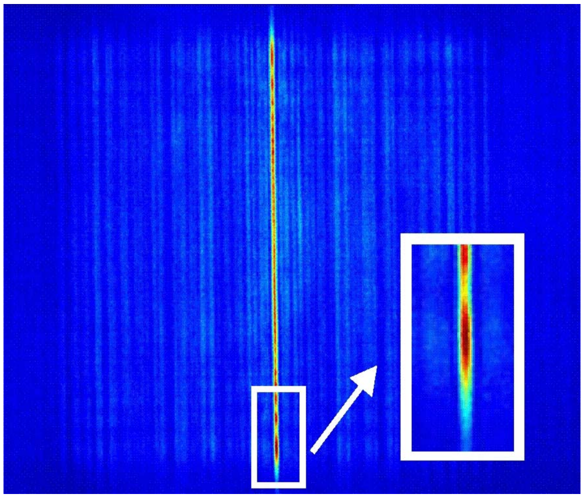


Figure 3 Intensity distribution from binary amplitude CGH of a line in space

A prominent line is obtained, but there are significant secondary fringes, both to the sides and at the ends of the line. Figure 4 shows the intensity cross-section from this image. It can be shown to have a *sinc*^{2} profile [15] in addition to noise generated by the binarisation process.

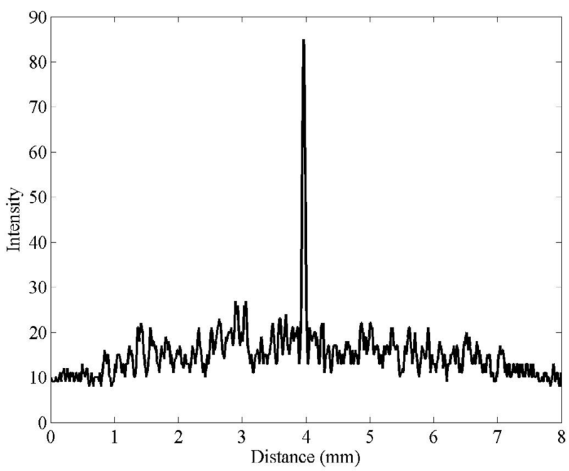


Figure 4 Intensity cross-section from a binary amplitude CGH of a line in space

The image is good enough to form a line in photoresist and to pattern a line (Figure 5), although control of line width is difficult (particularly when a wider line is required) and the line termination is far too imprecise for the results to find practical application.

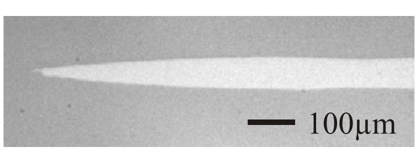
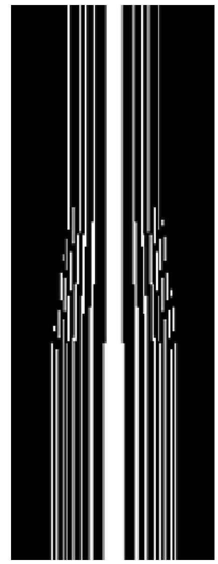


Figure 5 End section of a gold line imaged onto a glass substrate using a binary amplitude CGH

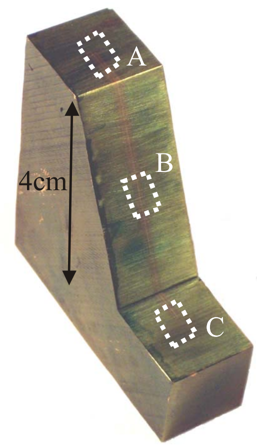
Imaging a line onto a sloping surface involves modifying (1) to include the variation in z along the line:

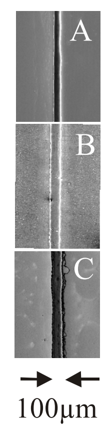
$$H(x,y) = \exp\left(j\frac{\pi}{\lambda z(x)} y^2 \right) \tag{2}$$

Stitching together CGHs calculated using truncated forms of (1) and (2) we have already demonstrated the patterning of a 100µm wide line over a 40mm-step (Figure 6) [16].



(a) Binary amplitude CGH





(b) Line patterned on block (c) Magnified views

Figure 6 Patterning of a three-segment line (binary amplitude)

It is possible to make a CGH using the binarised phase components of (1) rather than the amplitude components. We have achieved this by patterning (using a dry etch technique) a layer of PMMA spun onto a mask blank. The refractive index of PMMA (n~1.5) means that a π-radians phase shift is achieved in a layer thickness equal to that of the illuminating radiation (403nm). The resulting projected image still has a *sinc*^{2} profile, but the signal to noise ratio from the binary phase pattern is 8.5 as opposed to 4.4 for the binary amplitude pattern [15] (see Figure 7), increasing the manufacturing process latitude.

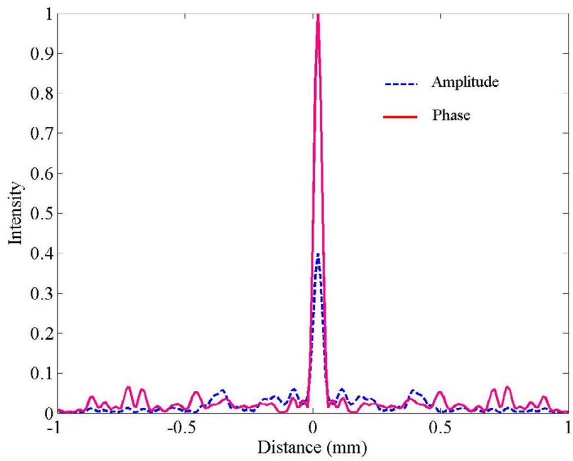


Figure 7 Simulated intensity cross sections from binary phase and amplitude CGHs of lines in space

In binarising the CGH pattern, a crucial benefit has arisen in the suppression of the higher diffraction-order images formed by the mask. Typically, a CGH produces a number of copies of the desired image centred at different spatial locations. This corresponds to the "spectral islands" that arise when a continuous function is sampled. Continuing the analogy, a CGH must then be sampled at a frequency high enough to separate the various image copies spatially, so that the primary image can be recovered by appropriate filtering. The upshot is that the minimum achievable mask-substrate separation for a given CGH pixel spacing increases as the size of the image region increases; this figure can easily exceed 1m for a typical PCB geometry. However, the use of binary line segment patterns such as that of Figure 6 and the higher image-order suppression that results means that lines can be imaged at arbitrary mask-substrate separations. Although higher image-orders may then interfere with other tracks imaged elsewhere, their low intensity means that the photoresist can successfully filter out this effect.

Pseudo greyscale CGHs

Figure 8 shows the comparison of simulated intensity distribution of a line image from a binary amplitude CGH with that of the ideal line. For these binary amplitude or phase masks the intensity falls off as *sinc*^{2} on moving away from the centre of the line, making control of line width within the photolithographic process difficult. Additional side fringes are also present.

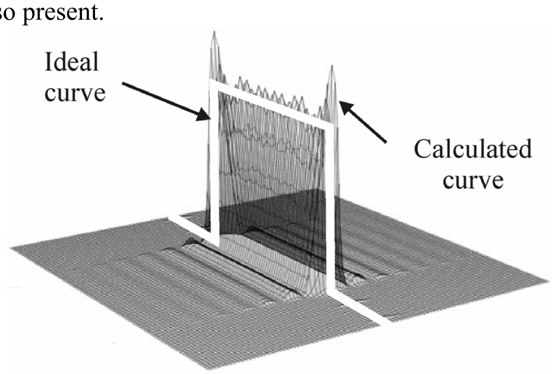


Figure 8 Simulated intensity distribution from binary amplitude or binary phase CGH

By calculating the complex-valued diffraction pattern generated by a well-defined rectangular feature at a given orientation in space, rather than the distribution from a *sinc*^{2} line profile, a much more precisely defined feature can be imaged [17]. Unfortunately, the resulting diffraction pattern is difficult to produce using conventional processes; a more readily produced alternative is to take the real part of the complex distribution and capture this in the holographic mask. This results in a need to encode a range of greyscale values in the hologram, which has been achieved here using a pseudo-greyscale technique whereby the area of the aperture at each pixel represents the grey level (Figure 9). Because the real-valued diffraction pattern takes on both positive and negative values, and because the introduction of a bias term to offset the negative parts of the mask results in additional unwanted noise in the image, it has also been found necessary to superimpose a binary phase layer (Figure 9 and Figure 10) to capture the full range of the real axis and to produce a sufficiently well defined image.

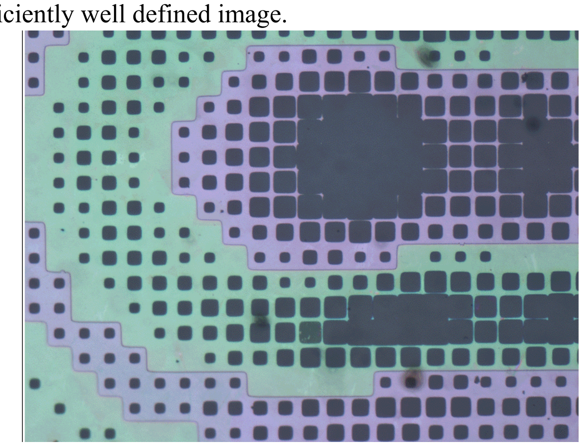


Figure 9 Section of binary phase/pseudo greyscale amplitude CGH for a line in space

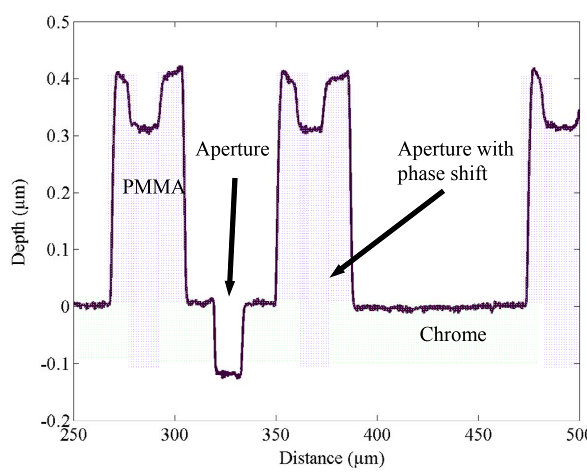


Figure 10 Surface profile of section of a binary phase/pseudo greyscale amplitude CGH mask

The resulting image (Figure 11) is much closer to that required, with much lower intensity side bands (Figure 12). Note, however, that the use of apertures to modulate the transmittance of the mask has led to the introduction of more significant first-order images surrounding the primary rectangular feature. The relative intensity of these features is low, but they may present problems when complex images comprising many such rectangular shapes are created.

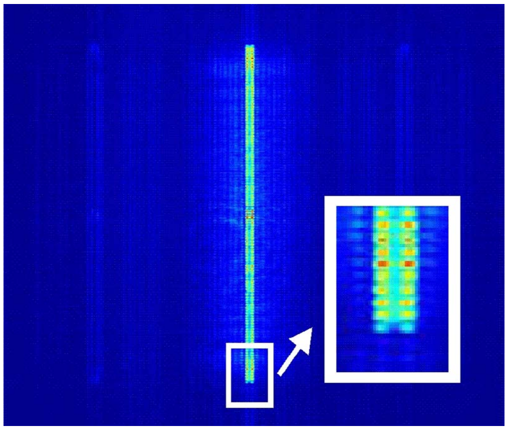


Figure 11 A pseudo-colour intensity distribution from binary phase/pseudo greyscale CGH

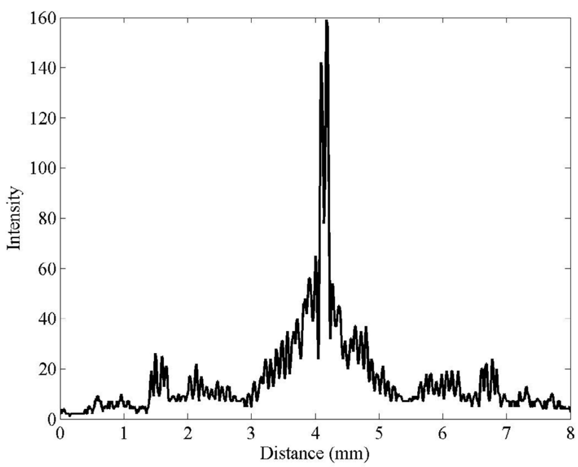


Figure 12 Intensity cross section for binary phase/pseudo greyscale CGH

Using the intensity distribution in Figure 11 to expose the EPDR results in the metallised line (Figure 13), showing a much better line shape (width and definition of the end point) in comparison to patterned lines produced with the binary phase or amplitude masks (Figure 5). However, the lines formed still suffer from a regular width variation, corresponding to the spatial frequency of the pixels in the mask.

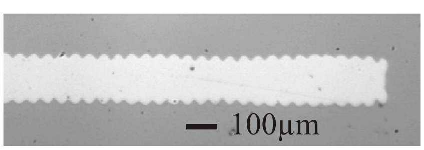


Figure 13 A gold line on silicon from binary phase/pseudo greyscale CGH

CGHs using slits

The regular width variation depicted in Figure 13 can be eliminated by implementing the greyscale amplitude as variable-width slits instead of apertures (Figure 14). This has the effect of virtually eliminating the higher order features that appear above and below the primary rectangular feature and Figure 15 demonstrates how the slit-based mask is able to produce an extremely well defined rectangular feature. However, this approach does increase the intensity of the first-order rectangle images that appear to both sides (Figure 16 and Figure 17). Once again though, care must be taken with this approach since the higher image orders are liable to interfere with additional features when multiple line segments are required.

We suggest that the suppression of higher order images could be achieved by encoding grey scale intensity using graded-opacity pixels rather than the binary apertures described above, and that the signal to noise ratio could be further improved by extending the binary phase coding scheme to include multiple phase levels.

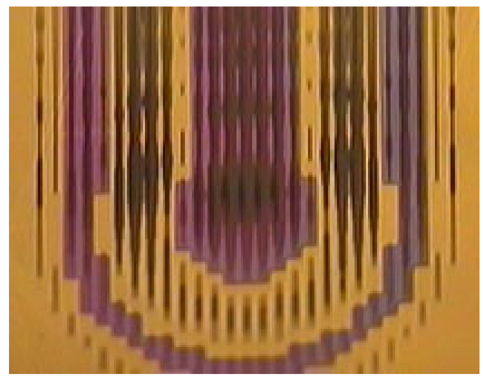


Figure 14 Binary phase/pseudo greyscale CGH using slits

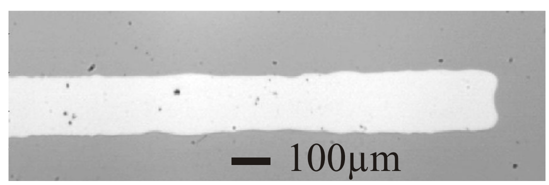


Figure 15: Gold line on silicon realised using binary phase/slits greyscale CGH

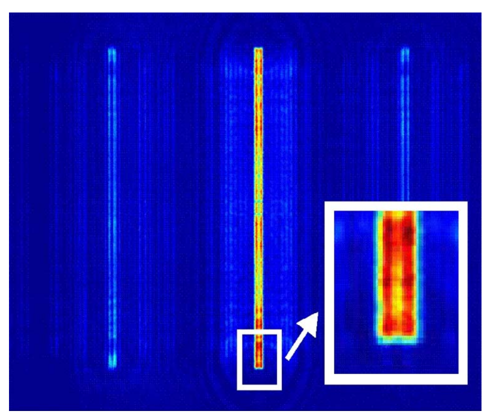


Figure 16 False colour intensity distribution from binary phase/slit greyscale CGH

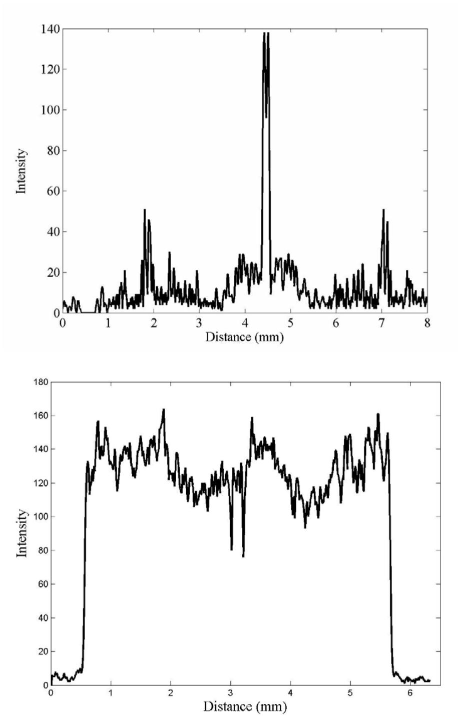


Figure 17 Horizontal and vertical cross-sections of images from slit amplitude/binary phase CGH

Conclusions

In this paper, we have presented a method for achieving fine-pitch photolithography on non-planar surfaces. The technique is based on the use of computer-generated holograms to create a three-dimensional light distribution that can be used to image virtually any topography. We have shown that our CGH enhancements make the projected image much more precise and by this means we can create a robust photolithographic process. We have demonstrated the patterning of 100µm wide tracks over a 40mm step at large distance from the mask. Many applications for the technique can be envisaged in the fields of microelectronic and micro-optical packaging and MEMS device fabrication. These are the subjects of ongoing research within our group.

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