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Coherent diffraction lithography: Periodic patterns via mask-based interference lithography

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Periodic structures, such as gratings and grids, are required in a variety of applications including spectroscopy, photonic and phononic devices, and as substrates for basic studies in materials science. Interference lithography readily forms periodic patterns in photoresist, but conventional approaches, using a Lloyd's mirror or Mach–Zehnder configuration, suffer from a number of shortcomings including difficulty in aligning patterns with respect to pre-existing structures on a substrate and difficulty in precisely repeating a given spatial period. Coherent diffraction lithography (CDL), a mask-based approach, utilizes the well-known Talbot effect to accurately replicate the one- or two-dimentional pattern on a mask by reimaging the mask pattern in photoresist. Moreover, with appropriate alignment marks on the mask, one can align the replicated pattern relative to pre-existing patterns on the substrate. The authors describe the design, construction, and utilization of a dedicated CDL apparatus that permits replication, at a well-defined mask-substrate gap, of the periodic structure of a phase mask. The system also incorporates interferometric-spatial-phase imaging for aligning the replicated pattern relative to fixed fiducials on a substrate. They obtained high quality replications of a mask pattern, consisting of a 600 nm period grating, from the 1st to the 52nd plane of reimaging, i.e., from 1.55 to 40.16 μm. © *2009 American Vacuum Society.* [DOI: 10.1116/1.3237093]

I. INTRODUCTION

Several forms of interference lithography (IL) have been described for producing large-area periodic and quasiperiodic patterns, including Mach–Zehnder,[1] Lloyd's mirror,[2] achromatic,[3] scanning-beam[4] and mask-based systems.[5] For mask-based forms based on the Talbot effect,[6] we coined the term coherent diffraction lithography (CDL).[7] In this article we describe the construction and experimental results of a CDL system that incorporates multilevel alignment to enable registration of the periodic patterns to fixed fiducials on a substrate. One of our objectives in pursuing CDL is the fabrication of three-dimensional (3D) photonic crystals based on the stacking of prepatterned membranes.[8] The individual membranes will be patterned with a fourfold-symmetric pattern of holes and a fourfold-symmetric pattern of posts, having the same periodicity in X and Y, but shifted in phase, as illustrated in Fig. 1. Figure 1 also depicts the stacking of the individually patterned membranes to form a 3D photonic-crystal structure. The membranes also contain alignment marks so that the desired phase shift between successive membrane layers can be achieved during the stacking process. Deviation from perfect periodicity, the so-called defects, can be introduced after CDL patterning by scanning-electron-beam lithography or other means, e.g., zone-plate-array lithography.[9] Because the patterns on individual membranes are primarily periodic and large area, IL is considered the most efficient means of patterning. Aside from scanning-beam-interference lithography (SBIL),[4] CDL is the only other IL method that would enable one to align the periodic patterns relative to fixed fiducials on a substrate.

II. CDL

Figures 2(a) and 2(b) show a schematic, as well as a photograph, of the CDL system we constructed. The source is a GaN diode laser operating at 405 nm. The laser light is spatially filtered with a 10 μm pinhole, expanded and collimated. The collimated light irradiates a CDL mask and projects the image onto a photoresist-coated substrate.

The CDL masks were 6.4 mm thick fused-silica plate, patterned with either gratings or grids. The exposure of the periodic pattern of the CDL mask is done by one of the other IL methods, preferably either SBIL or the Mach–Zehnder, since both of these can produce large-area patterns that are spatially coherent. (The Lloyd's mirror system produces patterns with intrinsic, albeit small, distortion.) The Mach–Zehnder system produces a hyperbolic phase progression[1] unless the substrate is suitably flexed,[10] while the SBIL can produce a linear phase progression. For simplicity in our initial tests, we used a Lloyd's mirror IL system in fabricating the CDL mask. The patterns were exposed at a spatial period of 600 nm in a trilayer stack consisting of 200 nm of an antireflection coating (ARC) (AZ Barli by Microchemicals), 25 nm of evaporated SiOx, and 180 nm of PFI-88 positive photoresist from Sumitomo. To reduce the effect of reflection from the back surface of the fused-silica substrate, the opposite side is coated with >600 nm of the AZ Barli ARC. Once exposed, the pattern was transferred into the fused silica using CF_4 reactive-ion etching (RIE).

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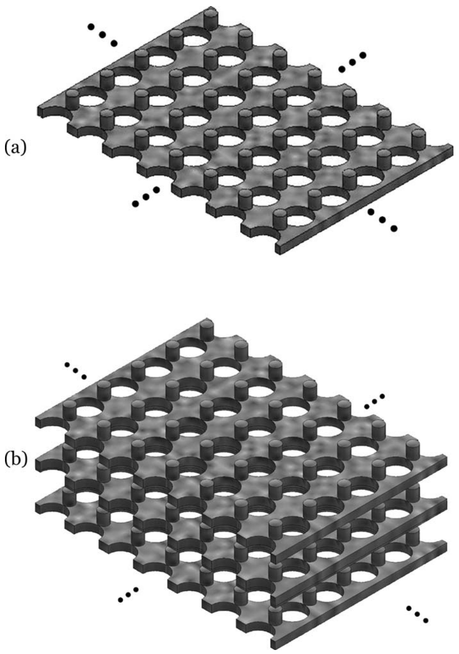

FIG. 1. Depiction of the pattern of holes and posts in membranes to be stacked to form a 3D photonic crystal. For Si membranes, and operation at a frequency corresponding to a free-space wavelength of 1400 nm, each layer has a periodicity in both X and Y of 600 nm and a layer thickness of 332 nm. In a given layer (a), the rods are located between two holes, and in a stack (b) the layers are shifted so that each post is located between the two holes in the layer above that do not already share an upper-layer rod between them.

For multilevel alignment and for setting the gap between the CDL mask and the substrate to be exposed, we used interferometric spatial-phase imaging (ISPI),[11] which is an alignment scheme with ~1 nm accuracy. The ISPI alignment marks were written onto the CDL mask by scanning-electron-beam lithography using polymethyl methacrylate as the resist. Using chromium as a hard mask the ISPI pattern was etched into the CDL mask using RIE.

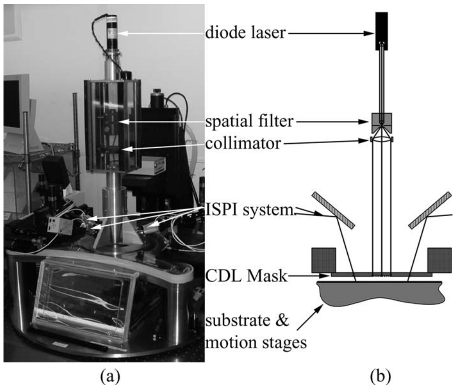

FIG. 2. (a) Photograph of the experimental configuration for CDL; (b) schematic corresponding the photograph in (a). The diode laser is a temperature and current stabilized 405 nm, 60 mW GaN laser from Power Technologies Inc. The spatial filter consists of a 0.19 NA lens and a 10 µm pinhole. After the spatial filter, a 5 cm diameter biconvex lens collimates the light incident on the CDL mask. Interferometric-spatial-phase imaging (ISPI) is used to align the CDL mask relative to the substrate. The mask holder has tip/tilt control while the substrate stage provided the x, y, and θ control.

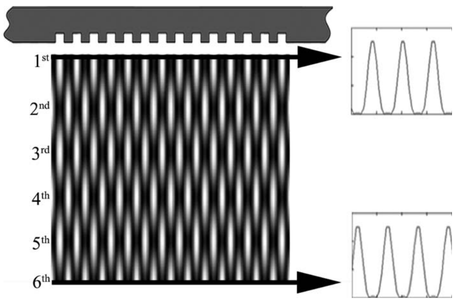

FIG. 3. Depiction of the Talbot effect. Downstream of the phase mask, interference of the zero, +1 and −1 diffracted beams produce intensity distributions that reproduce the grating periodicity p at discrete distances, referred to as planes of reimaging. The patterns associated with the even-numbered planes being laterally phase shifted by $p/2$ relative to the patterns of the odd-numbered planes.

III. TALBOT EFFECT

When a grating or a grid is illuminated with a coherent beam of light, as in our CDL system, diffraction produces interference effects downstream. The simplest case is when the zero-order beam is suppressed and only +1 and −1 diffracted beams propagate downstream of the CDL mask. This produces a doubling of the mask's spatial frequency.[12] In practice, it is very difficult to completely eliminate the zero-order beam when the period is close to the wavelength and so, in CDL, we retain the zero order. With the wavelength used (405 nm) and the spatial period of interest (600 nm), there is no second-order diffracted beam. As a result, the zero, +1, and −1 diffracted beams propagate downstream of the CDL mask and periodically get in phase and out of phase. This produces the interference pattern depicted in Fig. 3, which is known as the Talbot effect[6] and also as the "grating self-imaging effect." In the case described here, where we use only the zero, +1, and −1 orders, the separation distance between reimaging planes is given by the analytical expression

$$Z = \frac{1}{2}\frac{p^2}{\lambda}\left(1 + \sqrt{1 - \left(\frac{\lambda}{p}\right)^2}\right). \tag{1}$$

The factor of $\frac{1}{2}$ accounts for the distance between even and odd planes. It should also be noted that Eq. (1) reduces to the small-angle approximation for the so-called[6] half-Talbot distance when the radicand is unity.

IV. EXPERIMENTAL RESULTS

Exposures were done on Si substrates coated with a trilayer stack having a 200 nm thick bottom layer of BARLi ARC separated from a 180 nm thick layer of positive-tone resist, PFI-88 by a 25 nm thick interlayer of evaporated SiO_x. In order to investigate the Talbot effect at a variety of gaps between the CDL mask and the substrate, we did some exposures with the substrate tilted at an angle of ~5 mrad

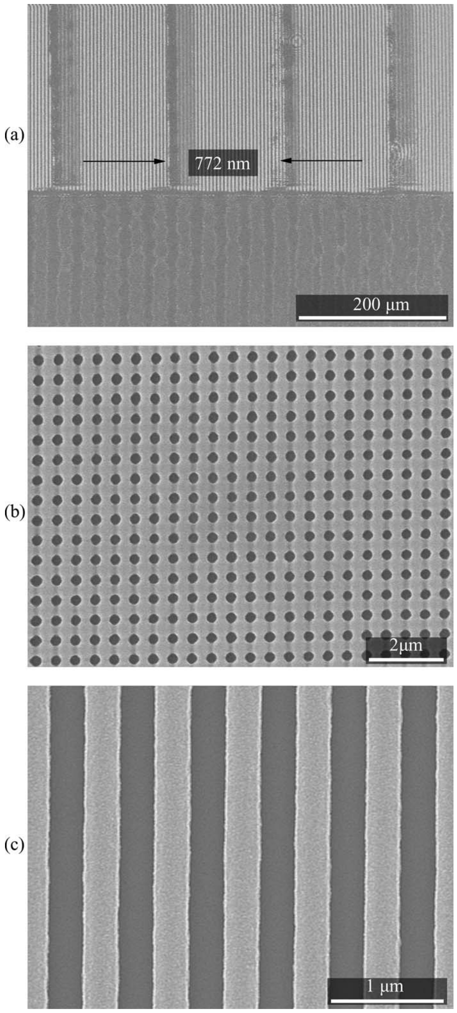

FIG. 4. Micrographs of experimental results from CDL exposures. In (a) and (b) the substrate was tilted at an angle relative to the mask plane and in (c) the substrate was at a uniform 2 μm gap from the mask. (a) Exposure in resist with ~5 mrad between the plane of a CDL grating mask and the substrate. The grating periodicity p is reproduced in distinct regions as the gap is increased, with a phase shift of $p/2$ between adjacent such regions. The dark bands, separated by 772 nm, correspond to doubling of the mask's spatial frequency (see Fig. 3). The grating is reproduced with maximum image contrast midway between the dark bands. Also shown, along the bottom of the micrograph, is a region of the mask that had no grating. This, in effect, is an interferogram of the wedge between the mask and substrate. (b) Micrograph at one of the reimaging planes for an angled exposure using a mask consisting of a 2D grid pattern. (c) Micrograph of a grating printed in resist at a uniform gap of 2 μm.

relative to the mask. Results are shown in Fig. 4 for the case where the CDL mask was a one-dimensional grating and a two-dimensional (2D) grid. In (a), one can see that reproduction of the grating occurs periodically as a function of gap, as predicted theoretically and depicted in Fig. 3. At any given plane of reimaging the depth over which the mask pattern is faithfully reproduced (equivalent to a depth of focus) depends on the relative magnitudes of the diffracted beams. In our experiments, that depth was >50% of the 772 nm distance between reimaging planes. We were able to obtain high quality reproduction of a 600 nm period grating from the 1st to the 52nd reimaging planes, i.e., from 1.55 to 40.16 μm. Figure 4(c) shows a grating printed at a uniform gap of 2 μm.

V. PRECISION OF REPLICATION

One of the advantages of the CDL technique relative to other forms of IL is the repeatability of reproduction on the substrate of the pattern on the mask. A deviation in source wavelength would not affect the pattern reproduced on the substrate, as it would for other forms of IL, unless the deviation was so large that either the first-order beams were cut off or second-order beams were generated.

We assumed above that the mask is illuminated with a normally incident plane wave. In practice, it is relatively easy to ensure that the beam is normal to within 1 mrad. Similarly, it is relatively easy to limit the divergence of the beam to 1 mrad. If the incident beam is inclined at a small angle of ~1 mrad, the pattern depicted in Fig. 3 would be inclined by the same angle. This would cause a proportional walkoff of the pattern relative to the ISPI marks. For replication at the second reimaging plane (see Fig. 3) this would correspond to a shift of 1.5 nm, which for most applications would be negligible.

If the beam illuminating the mask has some divergence, the distance downstream of the mask over which the mask is repeatedly reimaged would not be unlimited; the contrast of the fringes would degrade with distance from the mask. For a 600 nm period pattern and a divergence of 1 mrad, reproduction with good contrast at the reimaging planes would be present at distances out to a small multiple of 10 μm. Hence, one could choose to locate the substrate at any of several downstream reimaging planes. From the viewpoint of precision of replication, the most critical aspect of the CDL technique is to maintain the substrate parallel to the mask at a given reimaging plane. Clearly, deviation from exact replication would be linear in the angle between the mask and the substrate.

VI. CONCLUSION

We have constructed a system for interference lithography (IL) that utilizes the Talbot effect, a system we call coherent diffraction lithography (CDL). Because CDL employs a mask it permits aligning the exposed patterns relative to fixed fiducials on a substrate. Experimental results confirm analytical predictions for the gaps at which the mask pattern is reproduced.

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[1] J. Ferrera, M. L. Schattenburg, and H. I. Smith, J. Vac. Sci. Technol. B **14**, 4009 (1996).
[2] M. Walsh, "On the design of lithographic interferometers and their application," Ph.D. thesis, MIT, 2004, DSpace.mit.edu
[3] T. A. Savas, M. L. Schattenburg, J. M. Carter, and H. I. Smith, J. Vac. Sci. Technol. B **14**, 4167 (1996); T. A. Savas, Ph.D. thesis, MIT, 2003.
[4] G. S. Pati, R. K. Heilmann, P. T. Konkola, C. Joo, C. G. Chen, E. Murphy, and M. L. Schattenburg, J. Vac. Sci. Technol. B **20**, 2617 (2002).

[5] I. Bita, T. Choi, M. E. Walsh, H. I. Smith, and E. L. Thomas, Adv. Mater. **19**, 1403 (2007).
[6] E. Noponen and J. Turunen, Opt. Commun. **98**, 132 (1993).
[7] C. Zanke, M. Qi, and H. I. Smith, J. Vac. Sci. Technol. B **22**, 3352 (2004).
[8] A. A. Patel and H. I. Smith, J. Vac. Sci. Technol. B **25**, 2662 (2007).
[9] H. I. Smith, R. Menon, A. Patel, D. Chao, M. Walsh, and G. Barbastathis, Microelectron. Eng. **83**, 956 (2006).
[10] Michael E. Walsh and H. I. Smith, J. Vac. Sci. Technol. B **19**, 2347 (2001).
[11] E. E. Moon, L. Chen, P. N. Everett, M. K. Mondol, and H. I. Smith, J. Vac. Sci. Technol. B **21**, 3112 (2003).
[12] A. M. Hawryluk, H. I. Smith, R. M. Osgood, and D. J. Ehrlich, Opt. Lett. **7**, 402 (1982).