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Flexible Micro- and Nano-Patterning Tools for Photonics

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FLEXIBLE MICRO- AND NANO- PATTERNING TOOL FOR PHOTONICS

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Final Report

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PERIOD

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1.0 Introduction

The specific objective of this STTR was to improve and extend the performance of LumArray's maskless photolithography system, the ZP-150, by means of 8 tasks that included: enhancing the throughput; improving the spatial and temporal dose uniformity; dynamic tracking of the focal gap on non-flat substrates; improving the efficiency of 3D proximity-effect correction; designing a phase-shifting microlens for sub-100 nm patterning; writing of photonic devices, large-area computer-generated holograms and other diffractive-optical patterns.

The motivation was to provide the science and engineering community with a lowcost, highly flexible maskless photolithography tool that meets the needs of photonic systems for high-fidelity, long-range spatial-phase coherence, full-wafer coverage, 3D structuring, patterning on non-flat surfaces, and sub-100 nm resolution. The tool was to be compatible with both research and low-volume manufacturing of photonics, diffractive optics and electronics. This STTR responded to the DoD need for rapid turnaround on customized photonics and electronics, while also lowering cost and ensuring security.

2.0 Maskless photolithography compared to electron-beam lithography

Figure 1 is a schematic of the zone-plate-array lithography technology that is implemented in LumArray's ZP-150 system.



Figure 1: Schematic of zoneplate-array lithography (ZPAL), being commercialized by LumArray, Inc. A CW laser illuminates a spatial-light modulator, each pixel of which controls the light intensity to one diffractive microlens of the array. By moving the stage under computer control, and intelligently modulating focalspot intensities, patterns of arbitrary geometry are written.

Figure 2 shows the ZP-150 installed at NIST and the system within its environmental enclosure.



Figure 2: (left) Photograph of the ZP-150 system at NIST prior to installing the environmental enclosure; note the compactness of the system. The operator is inputting pattern data. The item directly above the granite base is the air-bearing X-Y stage with a range of 10 inches (254 mm) directly out of the page and 8 inches (200 mm) left and right. Above the stage are the optical components. Computer systems are located remotely. (right) Photo of LumArray's ZP-150TM system within its 5 ft x 3.5 ft environmental enclosure.

The advantages of maskless photolithography relative to scanning-electronbeam lithography, which is also maskless, are summarized in Table 1.

Table 1

Why photons are preferred over electrons for maskless lithography

- Photons are not deflected by stray electric and magnetic fields
- There is no mutual repulsion among photon
- Photolithography is done in air not vacuum, thus minimizing thermal effects
- There is no limit on photon flux density
- Lasers provide very high flux density
- Photons have low energies; 6 eV @ 193 nm vs 100 keV for electrons
- "Shot noise" is negligible with photons but highly significant for electrons
- Writing rate goes as the 2nd power of resolution, not the 4th as with electrons
- "Wavelength-selective chemistry" can be applied to kill reflections & beat the so-called diffraction limit
- Optical phase and polarization can be controlled & used to advantage (e.g., phase-shift masks and microlenses, wavefront engineering)
- Photolitography is extendable to 10 nm resolution via wavelength-selective chemistry

3.0 Improvements to the ZP-150 system

The major improvements made to the ZP-150 system under this STTR included: enhancements to the spatial and temporal dose uniformity; development of dynamic tracking of the focal gap so as to accommodate non-flat substrates; enhancement of the computational efficiency of proximity-effect correction; and the design of a phaseshifting diffractive-optical microlens that could enable sub-100 nm resolution.

With regard to dynamic tracking of the focal gap, we first obtain a "wafer profile" by scanning the substrate while holding constant the pressure of the air bearing stage. Four gap sensors collect data on the focal gap as a function of position. During exposure, we adjust the focal gap by varying the pressure of the air bearing stage. This moves the substrate either closer to the zone-plate array or further away. Figure 3 shows data obtained with and without dynamic tracking.



Figure 3: (Left) Results of a scan across a single line of a wedged substrate back and forth about 8 times. The width of the substrate is about 50mm. (The blank areas at the top and bottom of the scan indicate overscan.) (Right) Scans back and forth across the same regions while the pressure of the air bearing is adjusted, based on data from a prior wafer-profile scan. Residual gap errors are <500nm, which we believe is due primarily to non-linearity in the air-pressure response. This is well within the depth of focus or our current microlenses which have numerical apartures (NA) of 0.6.

4.0 Reduction of crosstalk between adjacent focal spots

The pixels of the spatial-light modulator that direct light to the individual microlenses of the zone-plate array are miniature diffraction gratings, consisting of only 3 spatial periods, as shown in Fig. 4. The spatial light modulator is manufactured by Silicon Light Machines.



Figure 4: Depiction of a single pixel of the spatial light modulator (SLM), called a grating light valve (GLV), used in LumArray's ZP-150 system. The full modulator has 1086 such GLV's. Note that the GLV is a diffraction grating whose efficiency is variable, i.e., with no displacement of the 3 movable ribbons only the zero-order is produced. With full deflection of the 3 ribbons the first-order diffracted beams have their maximum intensities.

Because each GLV diffraction grating consists of only 3 periods, the diffractive spread of the beams is relatively large. As a result, a beam that is directed from one pixel of the SLM to one of the zone-plate microlenses of the array has some leakage onto adjacent microlenses. This "crosstalk" leads to difficulty in properly exposing both features of a pattern, especially dense, high-resolution features.

The goal of crosstalk correction is to achieve a desired focal-spot intensity, regardless of the intensity values of adjacent focal spots. We decided to do this correction in software via the commands given to the pixels of the spatial-light modulator. That is, the software takes into account the contribution to a given focal spot intensity from the SLM pixels that direct light to adjacent zone-plate microlenses. The results are depicted in Figs. 5 and 6.



Figure 5: *Plot of (top) the correction being applied for Pixel# 441 of the spatial-light modulator in order to achieve intensity level 240, when its left and right neighbors ramp from 0 to 240 in steps of 20. (bottom) Residual error after the correction has been applied.* In Fig. 5, the top plot represents the amount of correction being applied for Pixel# 441 to achieve intensity level 240, when its left and right neighbors ramp from 0 to 240 in steps of 20. The bottom plot represents the residual error after the correction has been applied. The correction being applied is as much as 15 gray levels, out of a total of 255, and the residual error is only a few gray levels. The applied correction reduced the standard deviation of the residual-error from 13.8 to 2.4. Note that the correction is clipped at 15. This is because the max level of output is limited to 255 (255 - 240 = 15).



The plot in Fig. 6 shows similar result for pixel #441 at intensity level 160. As a result of applying the correction the standard deviation of the residual error was reduced from 8.3 to 1.2. Such reduction in residual error will significantly improve exposure results, especially for high-resolution, dense features.

5.0 3D proximity-effect correction

At the University of Utah, a new approach to proximity-effect correction (PEC) was developed that applies to 3D structures. The starting point of the simulation is a detailed model of the 3D point-spread function (3D PSF), i.e., the 3D distribution of light in the focal volume. The 3D PSF is convolved with the designed pattern to give an aerial image. This, in turn, is convolved with the nonlinear dissolution behavior of the photoresist.

To illustrate the efficacy of the proximity-effect correction, we chose a 3D woodpile structure, which is well known to exhibit photonic-bandgap response. The woodpile consists of gratings oriented along X from Z=0 to 100mm and gratings oriented along Y for Z=125mm to 225mm. The simulation results are summarized in Figure 7.



Figure 7: Simulation results for a "woodpile" geometry as a function of depth, *Z*. Columns (b) to (e) are without proximity-effect correction (PEC), while columns (f) to (i) show the result of applying PEC. A photoresist absorption coefficient of 2.2885e-03 μm^{-1} is employed. Column (a) is the designed pattern. Colums (b) and (f) represent the applied dose matrix. Columns (c) and (g) show the exposure distribution. Columns (d) and (h) show the resulting exposure image. Columns (e) and (i) show the error maps.

XY planes at various values of Z are illustrated in each vertical column. For instance, the design pattern is shown in Fig. 7(a). The dose distribution without PEC is shown in Fig. 7(b). The corresponding aerial image is in Fig. 7(c). The final exposed pattern is shown in Fig. 7(d). Finally, an error map, i.e., the difference between the exposed pattern and the designed pattern, is shown in Fig. 7(e). Without PEC, there are large errors particularly when Z is large. Once we apply our 3D PEC algorithm, the dose distribution is modified as in Fig. 7(f). The corresponding aerial images are shown in Fig. 7(g) and the final exposed images are shown in Fig. 7(h). The error maps are shown in Fig. 7(i). As can be seen, the PEC algorithm is able to correct most of the errors. This algorithm is also computationally very efficient.

6.0 Demonstrations of photolithographic efficacy

In addition to system improvements, lithographic efficacy was demonstrated through the writing of photonic-device patterns, computer-generated holograms, largearea diffraction gratings, and CMOS gate array patterns. These tasks are illustrated in in the following figures.



Figure 8: (*A*) Photograph of a 42 mm x 42 mm computer-generated hologram written on the ZP-150. Minimum features are ~375nm. (B) Micrograph of ring resonator pattern with output coupler. Note the ability to fabricate curved structures with good linewidth control.

Figure 9 shows a small region of the computer-generated hologram in Fig. 8 The minimum linewidth was about 0.4 micron.



Figure 9: Portion of the computer-generated hologram in Fig 8, showing linewidths of about 0.4 microns.

A unique feature of LumArray's ZP-150 is an ability to correct in software for pattern distortion. This is illustrated in Fig. 10.



Figure 10: (*A*) Example of a large-area diffraction grating written for, and tested at, Lawrence Berkeley Lab (LBL) as part of a collaboration to demonstrate correction in software for systematic phase deviations. (B) The line-placement error shows an improvement of about 4X over the initial error to ~+-30nm over an 80 mm-long grating. Revisions to the correction scheme, based entirely on software knowledge of systematic system errors, will result in further reduction of distortion.



Figure 11:(*left*) Optical micrograph of a portion of a 1-micron CMOS gate array, demonstrating good patterning quality over substrate topography. (right) Interleaved combs for alignment qualification showing no apparent error in centration.



Figure 12: Resolution tests using microlenses with NA = 0.6. The 0.5 micron lines are well resolved.

Subsequent to the work shown in Figs. 8 to 12, we discovered errors in the way we fabricated our diffractive optical Fresnel microlenses. We've also solved problems associated with crosstalk between beams from the spatial-light modulator, as described in Section 4 above. These improvements are expected to significantly enhance resolution and image contrast.

7.0 Summary and impact for DoD

A plethora of modern technologies, including photonics, electronics, MEMS and bioengineering depend critically on lithography. However, most commercial lithography tools were developed explicitly to meet the needs of high-volume semiconductor manufacturing. This contrasts with the DoD's urgent need for rapid turnaround and low-volume manufacturing of custom components in on-shore secure facilities. This STTR provided support for improvements to LumArray's maskless photolithography system, the ZP-150, which was specifically designed to meet the requirements of research and low-volume manufacturing.

With regard to custom electronics at the finer nodes, Fig 13 illustrates LumArray's prospects for meeting DoD needs. Work in this direction is scheduled to be supported under a Phase 1 SBIR from DTRA.



Figure 13: Plot showing that if one employs a 1D-grid approach, LumArray's current configuration of the ZP-150 can make the "line cuts" (the critical step) down to the 45 nm node. It would be a small step to improve the numerical aperture (NA) of the microlenses on the ZP-150 to NA= 0.9, thereby meeting requirements for the 32 nm node. A wavelength of 355 nm, and the phase-shifted microlenses, investigated under this STTR, would make the 22 nm node accessible. Resolution-enhancement techniques such as Absorbance Modulation Optical Lithography (AMOL) would enable the 15 nm node to be accessed.

LumArray's maskless photolithography is clearly a disruptive technology. It circumvents the constraints of conventional mask-based optical-projection lithography and provides the flexibility to pattern a wide variety of devices. In addition, it can reduce turn-around time and lower cost on custom products, and enable designers to try out innovative ideas and new layouts. All the components of LumArray's system are either off the shelf or fabricated in LumArray's facility. Like other disruptive technologies (think digital cameras, cell phones and desk-top printers) LumArray's will give rise to applications not previously envisaged, once engineers are freed from the inflexibility of mask-based optical-projection lithography. At present, LumArray's disruptive technology is unique to the USA. Because it can play a critical role in National Security, careful thought should be given to ensuring that this technology thrives and remains on shore, entirely owned by on-shore interests.