Enabling nanoscale science and engineering via highly flexible, low-cost, maskless lithography

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ABSTRACT:

The role of lithography in the future of nanoscale science and engineering is to put high-density spatial information into nanoscale assemblies. Because information content determines the functionality of such assemblies, lithography will be a key enabler. Conventional lithographic techniques generally lack the flexibility, low cost and the resolution that research in nanoscale science and engineering requires. Although no single lithographic technique is likely to be a panacea, it is important to seek novel approaches that meet the needs of researchers, and open a path to directly manipulating nanoparticles and macromolecules. We review the various forms of lithography and focus special attention on maskless zone-plate-array lithography, assessing its impact, advantages and extendibility to the limits of the lithographic process.

Nanoscale assemblies will require control at the macromolecular level, and this has begun with research on templated self assembly. Going beyond that to the control and utilization of the information content of nanoparticles and molecules will require innovations whose origin is uncertain at this point.

Keywords: Maskless lithography, Zone-plate-array lithography

1. INTRODUCTION:

The information revolution, which has dramatically altered the world economies and our everyday lives via personal computers, email, the internet and wireless communication, is based upon integrated electronics, which in turn is based upon lithography. Lithography puts spatial information into a substrate, and it is this information that determines functionality. Lithography has been the key technology in the information revolution, and will certainly underpin future technological revolutions based on nanotechnology.

Table 1 lists the wide variety of lithography techniques available today or under investigation. No single technique is a panacea; all seem to have their advantages and disadvantages. In this article we discuss the important role of maskless lithography, both for direct writing of patterns on experimental substrates and for making masks for mask-based lithographic replication techniques.

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Table 1: Many Forms of Lithography

- Optical-projection lithography
- **Optical-rojection imaging of micromirror arrays**
- Contact photolithography (conformable and nonconformable)
- Plasmon-based lithography
- **Scanning e-beam and ion-beam lithographies (single and multibeam)**
- Projection e-beam and ion-beam lithography
- X-ray lithography (with and without synchrotron)
- Imprint lithography (thermal and step & flash)
- Soft lithography (PDMS and other)
- **Zone-plate-array lithography (linear and non-linear)**
- **Interference lithography (multiple forms)**
- **Scanning-beam interference lithography**
- **Scanning probe lithography**
- **Dip-pen lithography**
- DNA-based lithography
- Block-copolymer lithography
- Neutral atom lithography

Red / **Bold** ⇒ maskless

Ideally, a maskless lithography system should be highly flexible from the viewpoint of the pattern types that can be written and the substrate types that can be used. For example, it should be able to write patterns of arbitrary geometry, including circles and ellipses, on insulating substrates. The cost of a maskless-lithography tool should be low, especially for research applications, and the resolution should be high. Ideally, the tool should be capable of placement accuracy at the sub-1 nm level. There are several maskless lithography tools under development, as indicated in Table 1. Here we discuss and compare only scanning-electron-beam lithography (SEBL) and zone-plate-array lithography (ZPAL) for application to nanoscale science and engineering.

2. SCANNING-ELECTRON-BEAM LITHOGRAPHY:

Scanning-electron-beam lithography (SEBL) is widely used in research and to a limited extent in manufacturing [1]. The throughput is severely limited by the serial nature of the exposure. For example, let's assume a pixel size of 2x2nm for a minimum linewidth of 20 nm, and that shot noise considerations dictate 100 electrons per pixel. A thermal-field-emitter source can deliver about 1 nA into the 2x2 nm pixel. This in turn corresponds to an incrementing rate of 62.5 MHz. Hence, the time to expose an area of 1 cm^2 (assuming all pixels are addressed) would be 111 hours or almost 5 days! As pointed out by Pease, one can address this dilemma only by employing thousands of electron beams in parallel [2].

In addition to the problem of long exposure times, SEBL systems suffer from a problem of placement accuracy. Tables 2 and 3 summarize some of the factors that contribute to intrafield and interfield placement errors, respectively. Hastings et al. have proposed and demonstrated a solution to the placement problem called spatial-phase-locked e-beam lithography [3]. Results are shown in Fig. 1. In brief, an electron transparent fiducial grid, produced by interference lithography and having long-range spatial-phase coherence, is placed on top of the electron-beam resist. A secondary-electron signal, collected from the grid as the beam is raster scanned, provides a feedback signal whose temporal phase can be related to the electron beam position. Based on this, a correction signal can be fed back to the beam deflection coils. It appears that sub-1nm placement accuracy can be achieved by the SPLEBL technique, and that it would enable significant savings in the cost and complexity of an e-beam lithography system, as well as more relaxed requirements on stray field and vibration isolation.

Table 2: Sources of intrafield placement errors:

- Deflection distortion due to coil optics
- Deflection distortion due to electronics (e.g. DAC errors)
- Lens distortion (barrel, pincushion, aberrations)
- Environmental disturbances (thermal and mechanical)
- Electrical charging (resist, sample, dust, system parts)
- Stray magnetic fields
- Thermal gradients (vacuum is a good insulator)
- Mutual repulsion of electrons

Table 3: Sources of interfield (i.e. stitching) errors:

- Mismatch of length scales (deflector and interferometer)
- Rotation of deflection field relative to sample or stage
- Non flatness of stage mirrors
- Non orthogonality of stage mirrors
- Non rectilinear stage motion
- Temperature gradients
- Mechanical vibrations

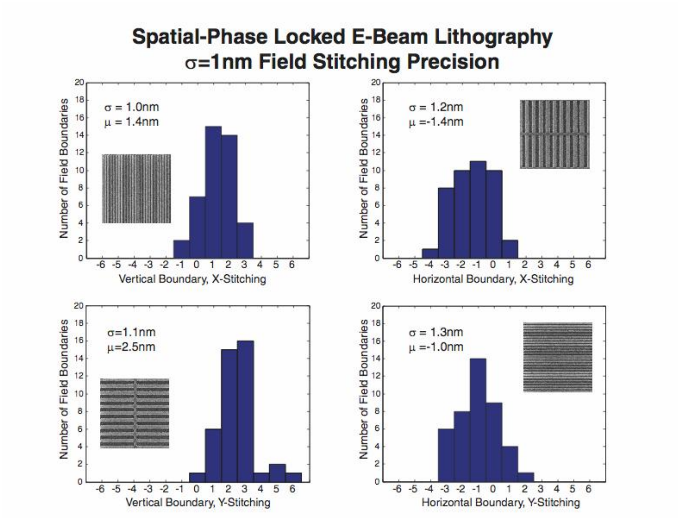

Figure 1. Histograms of field-stitching errors obtained with real-time spatial-phase locked e-beam lithography (global grid mode). Both x- and y-stitching errors are shown for the horizontal and vertical field boundaries. The mean and standard deviations are given on each histogram. We believe that intrafield distortion (which was corrected in software) was a limiting factor in these results.

Given that spatial-phase locking is required to achieve nanometer-level placement accuracy in a single-beam system, and that there is no reason to believe that a multiple-e-beam system would be more stable than a single-beam system, it appear that spatial-phase locking would be required in any multiple-beam system. This will be a daunting task for systems employing thousands of beams. To date, no initiative has been taken to incorporate spatial-phase locking in multibeam systems. It appears that the availability of multi-electron-beam-based maskless-lithography systems is still a long way off.

3. ZONE-PLATE-ARRAY LITHOGRAPHY (ZPAL):

Zone-plate-array lithography (ZPAL) represents a totally new approach to maskless lithography, which has produced extensive experimental results over a very short time [4]. The ZPAL scheme is depicted in Fig. 2.   It employs an array

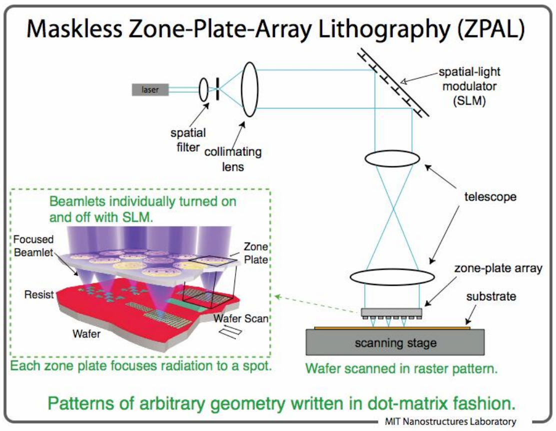

Figure 2: Schematic of the Zone-Plate-Array-Lithography (ZPAL) system. The spatial light modulator is an array of 1024 grating-light valves from Silicon Light Machines, the light source is a 400nm-wavelength GaN laser, the zone plates of the array are phase zone plates fabricated using SEBL and HSQ resist. The stage is moved under computer control enabling patterns of arbitrary geometry to be written in a dot-matrix fashion.

of diffractive optical lenses that focus incident light into on-axis spots. To date, the diffractive lenses have been phase zone plates, which focus 40% of the incident light into the first-order focus. The upstream spatial light modulators from Silicon Light Machines direct light to individual zone plates, and can vary the intensity from fully on to fully off in 256 steps. As the light to individual zone plates is modulated under computer control, the stage is moved, enabling the creation of patterns of arbitrary geometry in a “dot matrix” fashion.

Currently we use a commercially available GaN diode laser with a wavelength of 400 nm as the source. The zone plate arrays are made as phase zone plates using scanning-electron-beam lithography to expose hydrogen silsesquioxane (HSQ). Arrays with up to 1000 zones have been produced [5]. Numerical apertures (NA) up to 0.95 have been fabricated and tested. We found that an NA of 0.85 is optimal [5]. The usual relationship between wavelength and minimum half pitch applies:

$$W = k_1\, \lambda / NA, \tag{1}$$

where λ is the source wavelength, W is the minimum linewidth (i.e., half pitch) and k_1 is a proportionality factor.

Figure 3 shows lithographic results in which dense lines and spaces are written at about 1/3 the laser wavelength. It is noteworthy that these results are obtained without any filtering of the background radiation from the higher orders of the zone plate, which would improve contrast. If such filtering were desired, an order-sorting aperture could be placed between the zone plates and the substrate.

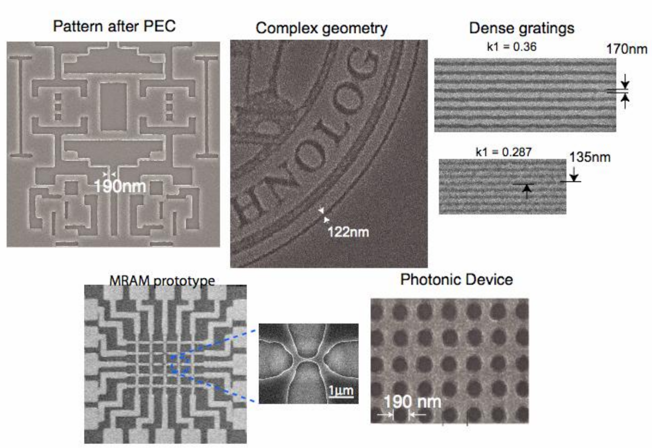

Figure 3: Experimental results obtained with the ZPAL system at MIT. From upper left clockwise: pattern written with proximity-effect correction (PEC); portion of the MIT seal with 122nm linewidth; dense lines and spaces written with k_1 as fine as 0.287; upper level of a 2-level magnetic random access memory prototype; magnified view showing the overlay of the upper level on the lower-level magnetic ring; portion of a 2D photonic crystal device pattern.

The ZPAL system at MIT has been used in the fabrication of a wide variety of devices and patterns of arbitrary geometry, as shown in Fig. 3; all obtained with the 400nm wavelength laser source. Based on these results, the MIT group has spun off a small company, Lumarray, Inc., to design and manufacture a ZPAL maskless optical lithography system (the model ZP150 A) with the specifications for the first generation given in Table 4 [6]. We believe that such a system will find wide usage in research and development, as an in-house mask maker, and as a complement to SEBL. With regard to the latter, the ZP150A could be used in a mix-and-match mode with SEBL, patterning feature above 150 nm and leaving the e-beam to pattern features below 150 nm. This will result in significant savings of time. The advanced overlay capability of the ZP150 will ensure seemless mix and match with SEBL.

Table 4: LumArray Model ZP150A Specifications

- High Resolution Optical Direct-write & Mask-write Tool
- Address unit: As small as 2.3 nm (via 8 bit grayscaling)
- Minimum feature size: 150nm (dense)
- Writing speed: over 1.5 mm^2/s
- Overlay accuracy: 20nm
- Placement accuracy: 15nm
- Geometries: Flexible (non-Manhattan possible)
- Laser source: 400nm
- Number of parallel beams: 1000
- Substrates: Silicon, glass or any flat surface up to 6" diameter
- Exposure: photoresist (I and G line)
- Field Size: flexible
- Scan method: serpentine
- Proximity-Effect Correction: Custom software provided
- Layout file format: GDS II compatible

The throughput of a ZPAL system depends linearly on the product of the number of pixels in the spatial-light modulator (which is also equal to the number of zone plates) and the addressing rate of the spatial-light modulator. The spatial-light modulator we are using, the Grating Light Valve from Silicon Light Machines, has only 1024 pixels. However, it appears straightforward to increase that number by a factor of 5 [7]. The addressing rate we currently use is 300kHz. Studies at Silicon Light Machines indicate that this can be increased to 5 MHz by a redesign of the grating light valves [7]. If both of these improvements were implemented, and assuming compatible addressing electronics, the throughput could be increased by a factor of about 80, i.e., forty 150 mm wafers/hr, or ten 300 mm wafers/hr.

4. SHORTER WAVELENGTHS:

One obvious approach to achieving finer feature sizes with ZPAL is to employ a shorter wavelength source since resolution scales linearly with wavelength, as indicated in equation (1). The excimer lasers used in optical-projection lithography have pulse rates in the few kilohertz range. Their use would severely limit the throughput of ZPAL, and for this reason CW lasers are preferred. CW lasers are available at wavelengths 365 nm and 266 nm, and a 198 nm CW laser is under development at Coherent, Inc. The zone plates for a 198nm wavelength would use the same material (i.e., SiO_2) as for the 400nm wavelength, and the same fabrication process. They would differ only in the depth of the phase step to compensate for the difference in refractive index. Also, to retain the same numerical aperture (e.g., 0.85) the outer zones of the zone plates would have a proportionately finer linewidth.

5. INCOHERENT EXPOSURE, (GOOD OR BAD?):

In ZPAL, exposure is done in a point-by-point manner, and hence there is no coherent relationship between one exposed spot and another. (Adjacent zone plates are coherently illuminated, but their focal spots are sufficiently far apart that coherent interference effects are negligible.) This is a significant advantage of ZPAL relative to optical projection schemes which use partially-coherent illumination to image a large array of contiguous pixels. For example, proximity-effect correction (PEC) is much simpler in ZPAL (see Fig. 4) because individual dot exposures are additive in *intensity* and hence highly efficient solutions are possible compared to the complexity of optical-proximity correction in partially-coherent imaging schemes. Also, the Rayleigh resolution limit, which dictates the minimum separation of two features (i.e., the pitch) does not apply in ZPAL. In a point-by-point exposure scheme, the minimum pitch depends only on the point-spread function. If the latter can be somehow compressed, the minimum pitch can be reduced proportionally. This is not true in partially-coherent imaging schemes.

6. FINER LINEWIDTHS VIA PHASE SHIFTING:

The phase-shift strategy, which is widely used in optical-projection lithography, can also be adapted for ZPAL, as shown in Fig. 4. In brief, a phase ring is illuminated with collimated light far upstream of the zone plates such that the demagnified image of the phase ring is slightly less than the width of the zone plate's focal spot. The resulting image is then a convolution of the normal point-spread function and a phase step, as indicated in the figure. The modified point-spread function has a narrower peak but higher sidelobes. This approach would have a resolution advantage when writing isolated lines or spaces, but not, in general, when writing patterns of arbitrary geometry.

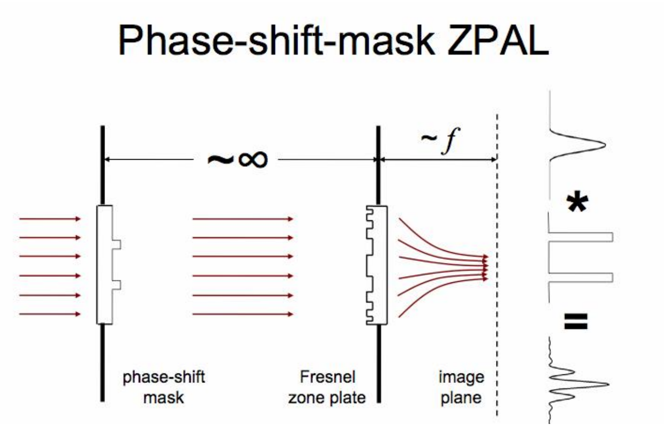

Figure 4: Schematic of a ZPAL phase-shifting strategy that would produce narrower peaks in the point-spread function, at the expense of higher sidelobes. This would be useful in exposing isolated lines or spaces but generally not for patterns of arbitrary geometry.

7. NONLINEAR APPROACHES TO RESOLUTION ENHANCEMENT:

In the early 1980's contrast-enhancement schemes were explored as a means of enhancing resolution in optical-projection lithography [8]. The point-by-point exposure strategy of ZPAL lends itself especially well to exploiting contrast enhancement and other nonlinear recording schemes. We have simulated one such scheme and plotted the results of that simulation in Fig. 5. (A description of nonlinear recording will be given in a subsequent publication.) Figure 5 indicates that by exploiting appropriate nonlinearities, together with incoherent, point-by-point exposure strategies, it should be possible to achieve feature sizes of $\lambda/20$ or better at spatial periods of $\lambda/10$. It is noteworthy that such nonlinearities are available only to photons because of the manner in which they interact with matter [9].

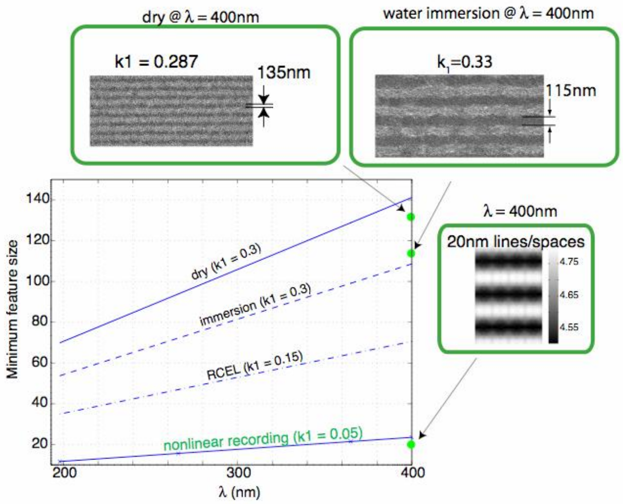

Figure 5: Plot of the minimum feature size versus wavelength for ZPAL. Experimental results associated with exposure in air and in water immersion [10] are indicated and shown in micrographs. Simulation results are shown for the non-linear recording for which feature size of $\lambda/20$ is predicted.

8. THE VIRTUES OF PHOTONS:

For decades it has been assumed that electrons would displace photons as the preferred particle for nanolithography. Certainly, the high resolution that is readily achieved with electron-beam exposure is highly attractive. However, as indicated in Table 4, there are significant advantages to photons. These have played a key role in the success of photon-based lithography up to now, and could well enable dramatic improvements in resolution, as predicted in Fig. 5.

Table 4: Advantages of Photons

- Photons have no charge. As a result there are no mutual interactions and no limits on the flux or flux density
- Photon energies are low compared to electrons, so damage is minimum
- Shot noise is generally negligible
- Phase, amplitude and polarization can be readily controlled and employed
- Wavelength can be reduced while keeping energy constant (refractive index effect)
- Nonlinear interactions in matter can be used to advantage

9. CONCLUSIONS:

Maskless lithography will play an important role in low-volume manufacturing, experimentation, design verification, research, and nanoscale science and engineering. Scanning-electron-beam lithography (SEBL) has had an enormous impact on mask making and nanostructures research. However, it suffers from limitations in throughput, placement accuracy and cost. Zone-plate-array lithography (ZPAL), using 400 nm-wavelength radiation, has shown very promising experimental results and will soon be commercially available. By exploiting optical nonlinearities it may be possible to extend the resolution of ZPAL to regions that are accessible today only with SEBL.

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