Patterning Technology for Nanomanufacturing

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ABSTRACT

Zone-plate-array lithography (ZPAL) was developed with the objective of combining the simplicity, throughput and accuracy of optical patterning with the flexibility and resolution of an electron-beam [1]. High throughput is achieved using a massively parallel array of photon beams, focused onto a substrate through high-numerical-aperture diffractive-optical lenses [2]. Patterns of arbitrary geometry are created in a dot-matrix fashion as the substrate is scanned across the focal plane. Incident light to each lens is modulated synchronously with the scanning of the stage using a spatial-light modulator upstream of the zone-plate array.

LumArray's ZP-150 beta-tool was designed with emphasis on flexibility for low-volume manufacturing, prototyping and R&D. The stability of photon optics enables pattern-placement errors to be corrected in software. Proximity-effect correction (PEC) is implemented for improved patterning fidelity. The ZP-150 beta tool is capable of resolution down to 150 nm linewidths in dense patterns. Absorbance-modulation offers the possibility of extending patterning resolution to ~20 nm, while retaining all the benefits of maskless optical lithography.

Keywords: lithography, maskless lithography, patterning, nanolithography

1 INTRODUCTION

In integrated electronics, photonics, microelectro-mechanical systems and nanofluidics, the lithographic process has been the key technology for creating structural complexity and high functionality in material systems. Unless something is invented to replace it, future systems based on nanoscale science and engineering will depend on lithographic patterning. Hence, it is important to develop modes of lithography specifically tuned to the needs and requirements of nanoscale science and engineering. Among these requirements are: reasonably low-cost tools; compatibility with rapid design changes; flexibility with respect to the types of patterns that can be created and the substrate types that can be employed; high resolution and placement accuracy at the nanometer level. In contrast to these requirements, the lithographic tools developed for the semiconductor industry cost a few tens of millions of dollars; they require a mask which, once made, cannot be changed; they achieve spatial periods of 74nm; they are designed to produce so-called "manhattan" geometries; and the material patterned is exclusively Si in the form of circular wafers up to 300 mm diameter.

2 ZPAL DEVELOPMENT

Because of the rigid constraints of the semiconductor-industry approach to lithography, we conceived and developed an alternative approach, called zone-plate-array lithography (ZPAL) that requires no mask, is relatively low cost, and is fully flexible with regard to pattern and substrate types [2]. Figure 1 is a schematic of ZPAL. High throughput is achieved using a massively-parallel array of photon beams, focused onto a substrate through high-numerical-aperture diffractive-optical lenses. Patterns of arbitrary geometry are created in a dot-matrix fashion as the substrate is scanned across the focal plane.

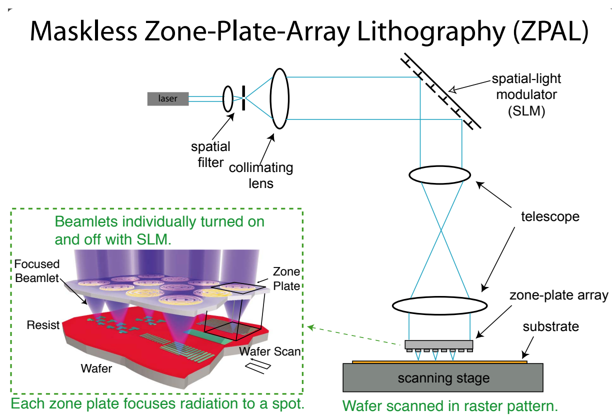

Figure 1: *Schematic of zone-plate-array lithography (ZPAL). A CW laser illuminates a spatial-light modulator (SLM). Each pixel of the SLM controls the level of light to one zone plate of the zone-plate array, adjusting the intensity from zero to maximum in a quasi-continuous manner. Such dose modulation enables* ***control*** *of feature size to the sub-1nm level. By moving the stage under computer control, complex patterns of arbitrary geometry are written in a dot-matrix fashion*

Each lens is modulated synchronously with the scan using a spatial-light modulator located upstream of the zone-plate array. Figure 2 shows an example of a pattern written with ZPAL.

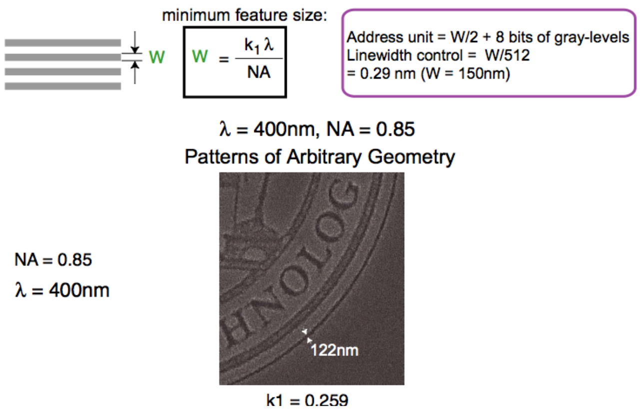

Figure 2: *Scanning-electron micrograph of a pattern produced in resist using ZPAL, illustrating the facility with which patterns of arbitrary geometry, including curved lines, can be written using the dot-matrix method.*

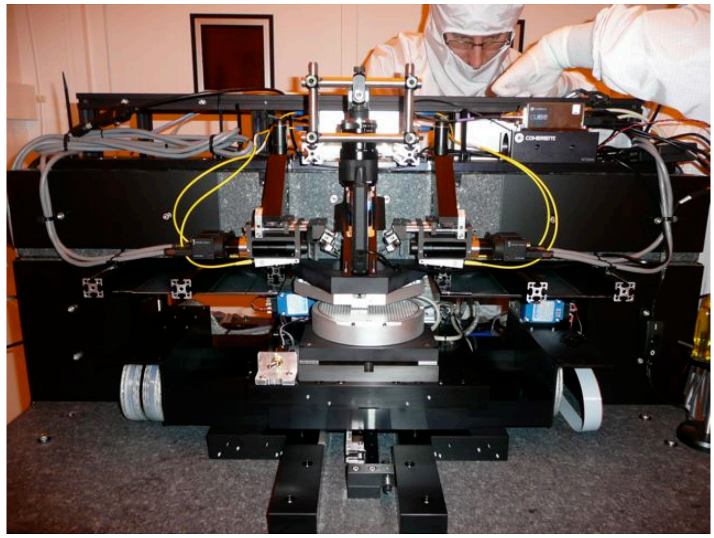

Figure 3: *Photograph of the ZP-150B under test.*

LumArray's ZP-150 was designed with emphasis on flexibility for low-volume manufacturing, prototyping and R&D. The advantages of this approach to nanolithography include: fast turn-around on pattern designs; ability to create non-manhattan geometries; a multiplicity of designs can be accommodated on the same substrate; the field of patterns is limited only by stage travel not by projection optics; potential for nanometer-level patterning accuracy and precision; correction of systematic errors via software; simple proximity-effect correction and linewidth control due to incoherent imaging; extendability to sub-20 nm resolution via photochromic chemistry (i.e., AMOL).

Many of the advantages of ZPAL are shared by another maskless lithography approach: scanning-electron-beam lithography (SEBL), which has the added advantage of deep-sub-100 nm focal-spot size, enabling sub-20 nm resolution. SEBL is widely used in research and development precisely because it is high resolution and does not require a mask. SEBL shares the virtue of flexibility we claim for ZPAL, however it has a number of disadvantages relative to a photon-based maskless system: a vacuum is required, leading to slow thermal stabilization; electrical charging of substrates and system parts leads to pattern distortion and electron-beam drift; the high energies employed (typically 30 to 100 keV) produce damage in many types of substrates.

Figure 3 is a photograph of LumArray's beta-stage maskless photolithography system (ZP-150) assembled in a clean room and under test.

The throughput of LumArray's ZP-150 is limited by the number of pixels, N, of the spatial light modulator (and hence the number of lenses in the zone-plate array), the update rate, R, of the modulator, and the exposure grid spacing, d. The area/sec exposed = NRd^2. In the ZP-150, N = 1086 and R = 290 kHz with 8 bit gray scale. The latter is essential for proximity-effect correction. Gray scaling also enables linewidths to be controlled to the nanometer level, much finer than d, the exposure-grid period. d is adjustable, depending on pattern resolution. For d = 75nm, the ZP-150 exposes at 1.5 mm/sec. A 150 mm wafer corresponds to 4 x 10^{12} bytes of information if fully exposed, which can be carried out in 2 hours.

Figure 4 is a block diagram of the ZP-150 system. Because there are 1086 lenses independently modulated while the stage scans across the full substrate, a high level of computer control is essential to quality patterning.

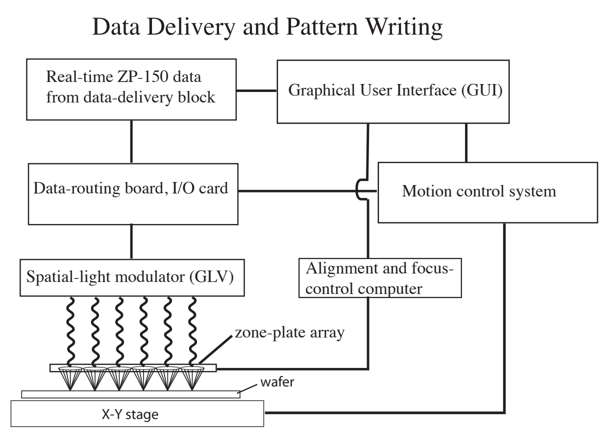

Figure 4: *Block diagram of the ZP-150 system.*

Figure 5 depicts how the focal-spot positions of all the lenses of the zone-plate array can be measured. Once measured, corrections for any systematic errors in the foci locations can be made in software. Similarly, any systematic errors in the scanning-stage travel can be measured and corrected in software.

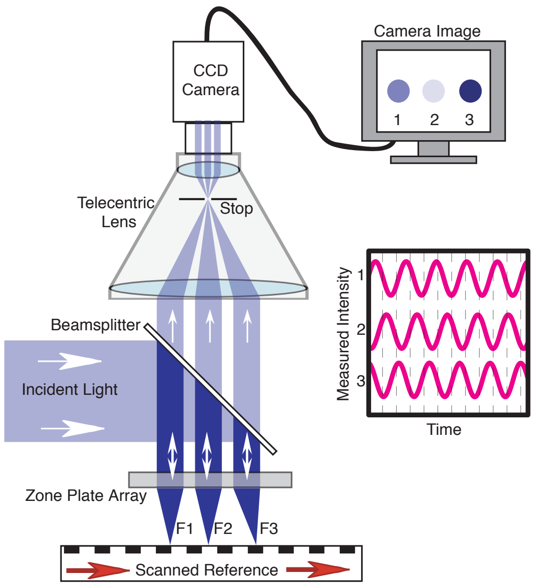

Figure 5: *Schematic illustrating how the focal spot positions from the zone-plate array can be determined from the phase of signals returned from a reference grating (produced by interference lithography [3]) scanned across the focal plane.*

Table 1

Min Feature Size	**200 nm with 0.85 NA lens array,**
# of Parallel Beams	1000
Dose Uniformity	<1% across all 1000 beams
Writing Speed	**1.5 mm^2/sec @ NA=0.85, 200 nm features** *higher at lower resolution*
Grayscale	8-bit grayscale in every pixel
Design Grid	5 nm
Position Resolution	0.6 nm
Max. Pattern Area	150 mm x 150 mm
Alignment / Overlay	< 50 nm
Field Size	150 mm x 150 mm
Focus	Optical Autofocus < 30 nm
Exposure Wavelength	405 nm
MiniEnvironment	ISO Class 5, temperature to 0.1˚C
Control Software:	LithoZone platform-independent, remote access web applic.
Layout Format	GDSII / OASIS
Computation	Nvidia GPU Server, 2 TeraFlops with 998 parallel cores
File Archive	30 TB PCI-express storage server

In order to enable ZPAL to approach the resolution achieved with scanning-electron-beam lithography (SEBL), we have explored a number of ways to circumvent the diffraction barrier of ordinary optics, which states that the minimum spot size is approximitately equal to 1/4 of the wavelength. For the 405 nm radiation currently employed in LumArray's ZP-150, this corresponds to a resolution limit of ~100 nm. Absorbtion-modulation-optical lithography (AMOL), depicted in Fig. 6, offers a means of going beyond this limit [4].

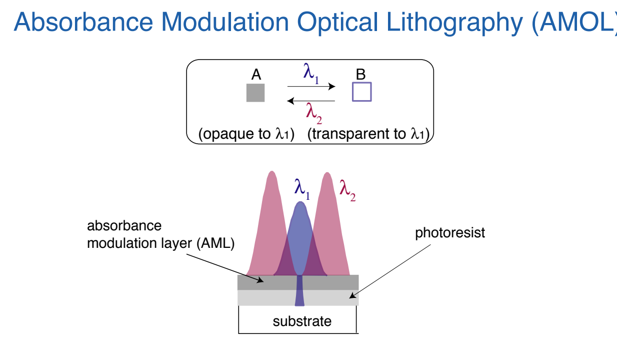

Figure 6: *Schematic of absorbance-modulation-optical lithography (AMOL). The photoresist is covered with an absorbance modulation layer (AML), composed of photochromic molecules which have the property that the short-wavelength, λ_1, (e.g., blue) light converts the AML from opaque to transparent, while the long-wavelength, λ_2, (e.g., red) light converts it from transparent to opaque. The λ_2 light is focused in the form of a donut with a central null. The null in λ_2 enables λ_1 to "bleach" a subwavelength aperture in the AML and pass into the photoresist, producing a sub-diffraction-limited exposed region. Patterns of arbitrary geometry can then be created via the overlapping of these sequentially exposed sub-wavelength spots [4].*

REFERENCES

[1] H. I. Smith, "A Proposal for Maskless, Zone-Plate-Array Nanolithography," J. Vac. Sci. Technol. B 14, 4318-4322 (1996).

[2] H. I. Smith, R. Menon, A. Patel, D. Chao, M. Walsh, and G. Barbastathis, "Zone-plate-array lithography: A low-cost complement or competitor to scanning-electron-beam lithography," Microelectronic Engineering, **vol. 83**, pp. 956-961 (2006).

[3] R. K. Heilmann, C. G. Chen, P. T. Konkola, and M. L. Schattenburg, Dimensional Metrology for Nanometer-scale Science and Engineering: Towards Sub-nanometer Accurate Encoders, Nanotechnology **15**, S504 (2004).

[4] R. Menon and H. I. Smith, "Absorbance modulation optical lithography (AMOL)," J. Opt. Soc. Amer. vol. **A 23**, 2290-2294 (2006); R. Menon, S. Y. Tsai, S. W. Thomas III, "Far-field generation of localized light fields using absorbance modulation, " Phys. Rev. Lett. **98**, 043905 (2007).