Zone-Plate-Array Lithography (ZPAL): Simulations for System Design

Rajesh Menon[*], D. J. D. Carter[+], Dario Gil[*], and Henry I. Smith[*]

[*]*Department of Electrical Engineering and Computer Science, Massachusetts Institute of technology, Cambridge, MA 02139.*
[+]*Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139.*

Abstract. We present a simulation study which examines the use of zone plates for lithography. Zone-Plate-Array Lithography (ZPAL) is a maskless lithography scheme that uses an array of shuttered zone plates to print arbitrary patterns in resist on a substrate. We have demonstrated a working ZPAL system in the UV regime, and are pursuing further experiments with the 4.5 nm X-ray to obtain smaller feature sizes. A general numerical simulation tool, based on the Fresnel-Kirchhoff diffraction theory, has been developed. A pattern will consist of many pixels exposed independently in the resist. Various zone plate and system parameters will affect the intensity distribution at the focal plane. We present simulation results which show the effect of these parameters on both the individual spots and exposed patterns.

INTRODUCTION

Zone-plate-array lithography (ZPAL) is a maskless lithography scheme that employs an array of shuttered zone plates to expose patterns of arbitrary geometry on a resist-coated substrate [1-4]. It is illustrated schematically in Fig. 1. By using an array of zone plates, and independently controlling their illumination while moving the substrate, one can achieve parallel writing in a dot-matrix fashion.

ZPAL borrows heavily from the field of X-ray microscopy, which over the last two decades has greatly advanced the technology of fabricating zone plates. Zone plates with minimum outer zone widths of sub-25 nm have been fabricated [5], and it is not unreasonable to expect that this will be further reduced in the future. Because the focal spot or point-spread-function of a zone plate is approximately equal to the width of the outermost zone, we believe that ZPAL can approach the limits of the lithographic process. For the lithography application we believe the optimal wavelength is 4.5 nm, i.e. just beyond the carbon-K edge. The 4.5 nm photon can be used to expose thick films of carbonaceous resist, while minimizing the proximity effects due to photoelectrons [6,7]. In fact, back in the late 1970's D. C. Flanders demonstrated that lines and spaces of 18 nm can be exposed in PMMA using C_K X-ray lithography in a contact mode [8]. Similar results have been obtained in the intervening years [9-12].

The main disadvantage of ZPAL at 4.5 nm wavelength is the necessity of using an undulator or similar collimated source of narrow-band radiation. However, such sources are clearly feasible [13]. The main challenges to developing ZPAL are the

multiplexed shuttering of the illumination to individual zone plates, and the problem of matching the efficiencies of all the zone plates of a large array. To address this problem of multiplexing, and our inaccessibility to an undulator, we have instead pursued ZPAL at UV wavelengths. In addition, we have developed ZPAL simulation tools which enable us to evaluate a variety of tradeoffs among such system and zone plate parameters as: source bandwidth, number of zones, fabrication errors, effects of order-sorting apertures, and number of zones per array vs. multiplexing rate.
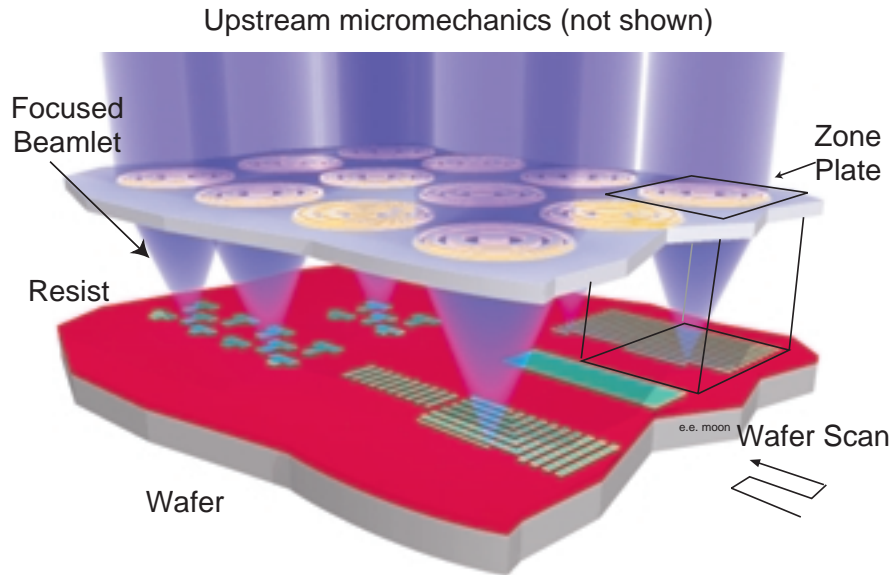

FIGURE 1. Schematic of zone-plate-array lithography (ZPAL). An array of zone plates focuses radiation beamlets onto a substrate. The individual beamlets are turned on and off by upstream micromechanics as the substrate is scanned under the array. In this way, patterns of arbitrary geometry can be created with a minimum linewidth equal to the minimum width of the outermost zone of the zone plates. Using 4.5 nm radiation, we estimate that lines and spaces of 20 nm should be achievable, provided that the zone plates can be fabricated.

THEORY

Fresnel-Kirchhoff diffraction theory [14-16] is used to calculate the point-spread-function of a zone plate. Scalar theory is suitable at the 4.5 nm wavelength since zone widths are much larger than the wavelength. However, at UV wavelengths, where we have done most of our experiments, the use of scalar theory is subject to question. Because the exposure of any arbitrary pattern is made up of separately exposed focal spots (pixels), we calculate the intensity distribution for any given pattern by adding the intensities of point-spread-functions. For simplicity, a binary clipping level was used to model the resist development.

The solution of the exposure/development simulation was implemented on an IBM-SP2 with 10 parallel processors. A Single Instruction Multiple Data (SIMD) model of parallelization was utilized in these simulations [17]. We can break up the problem spatially into numerous points, which are divided up among the available processors.

Each processor then computes the phase and amplitude of the diffracted wave at its assigned group of points. In this scalar model, the field at each point is independent of its neighbours and hence, inter-processor message passing is not necessary. Thus our problem is an obvious candidate for the SIMD parallel-processing model.

SIMULATONS

Fig. 2 compares a simulated spot compared to spots exposed in resist. Phase zone plates, with an outer zone width of 331 nm were used at an exposure wavelength of λ = 442 nm. The simulation tools took into account a 10% measured phase-shift error due to over-etching of the quartz during fabricaton. Despite the well- known inadequacy of scalar diffraction theory when wavelengths are comparable to or smaller than zone widths, our simulations come quite close to experimental results. This may reflect the fact that line-to-space ratios are close to unity near the outer zones [18].
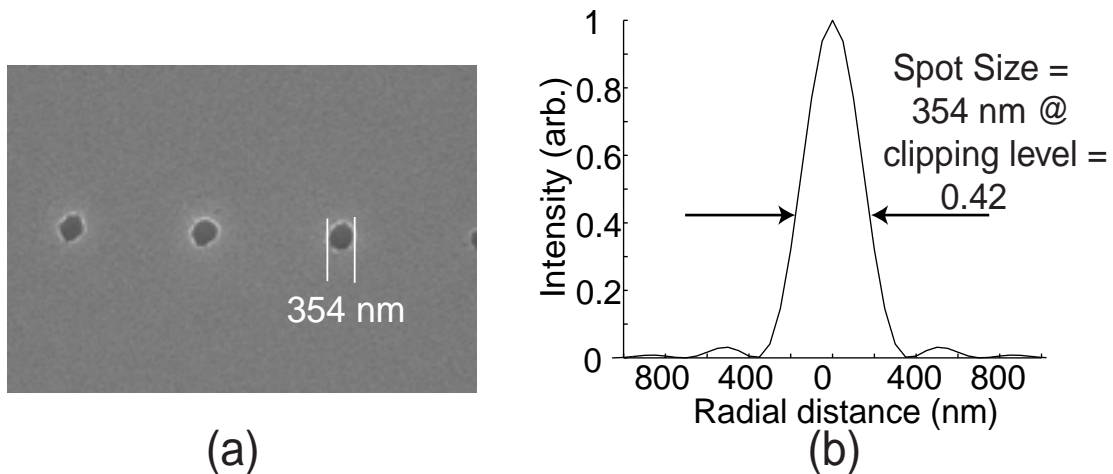

(a)

(b)

FIGURE 2. (a) Focal spots exposed and developed in photoresist, using the 442 nm wavelength HeCd laser, and zone plates fabricated in fused silica using direct-write e-beam lithography and reactive-ion etching. Zone plates of the array have 76 zones. They were etched within 10% of the π-phase depth. (b) Simulated point-spread-function for these zone plates, illustrating that a clipping level of 0.42 would produce the 354 nm diameter spot. The zone plates have a numerical aperture of 0.66.

In Fig.3, we show the comparison of our simulation to the micrograph of a pattern written in resist using the above-mentioned set of zone plates. The agreement is surprisingly good. Other patterns show similar agreement.

Fig. 4 shows a simulation assuming a collimated source of 4.5 nm X-rays having a bandwidth of 1/35 (e.g., an undulator on a synchrotron) [13]. The zone plates have 35 zones, the outer ones with a 50 nm pitch (i.e., 25 nm outer zone). Note that the proximity effect (i.e., the widening of linewidths in densely patterned areas) due to exposure contributions from nearby pixels is relatively small. In this case, no order-sorting apertures were assumed; they would significantly reduce the proximity effect.

Fig. 5 illustrates a possible order-sorting aperture configuration, with the higher-order blocker located about half way between the zone plate and the substrate.
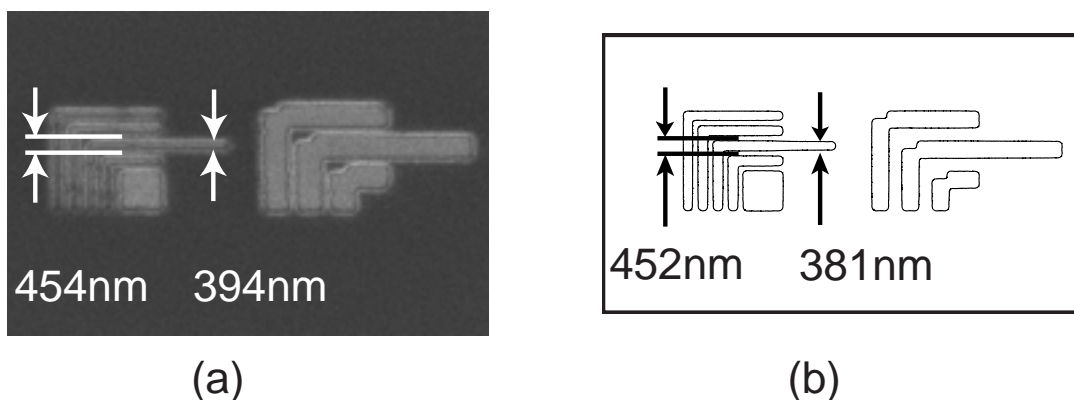

FIGURE 3.: (a) Scanning electron micrograph of a "nested L" pattern exposed and developed in Shipley 1813 photoresist, using UV ZPAL. (b) Simulation of the "nested L" exposure.
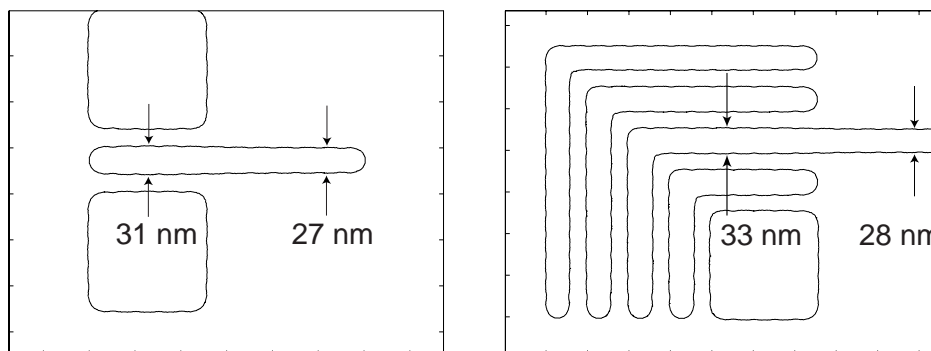

FIGURE 4.: Simulations of X-ray ZPAL exposures using a zone plate of 35 zones and a collimated source of 4.5 nm radiation, with a bandwidth of 1/35. The minimum zone width was 25 nm, corresponding to a focal distance of 19 μm. Line widening is due to background radiation from orders other than +1. (Order-sorting apertures would signifi-cantly reduce this proximity effect.)

Spot size, depth of focus, contrast and fidelity of patterns are some of the most important lithographic figures-of-merit. We can use our simulation tools to study how the system parameters such as source size, source bandwidth, demagnification and zone plate geometry affect these figures-of-merit.

Fig. 6(a) shows the intensity distribution for a grating, exposed using the same source and zone plate as in Fig. 4. Linewidths of 25 nm would be achieved by "clipping" at the intensity level of ~0.65. Perhaps more important is the exposure latitude. This is commonly expressed by means of the so-called Modulation Transfer Function (MTF), defined for a grating as
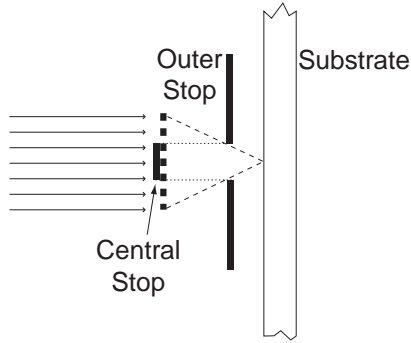
Figure 5.: Schematic of a zone plate, modified by the addition of a zero-order central stop, and an outer stop about mid way between the zone plate and the substrate. This stop effectively eliminates background effects due to the diffracted orders other than +1. The latter is focused on the substrate.

$$MTF = \frac{Max - Min}{Max + Min} \tag{1}$$

Fig. 6(b) plots the MTF as a function of the distance from optimal focus. In this case the focal length is 19 μm.
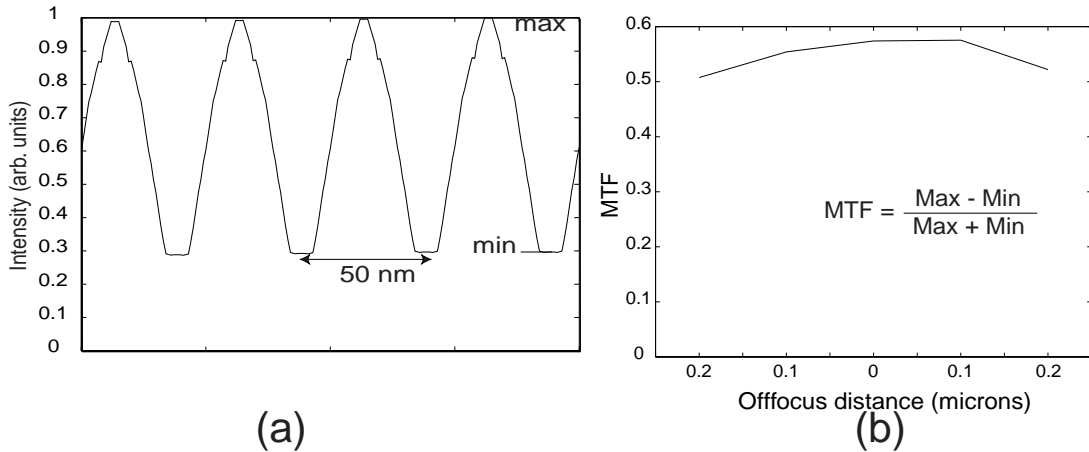

(a)

(b)

FIGURE 6.: (a) Intensity distribution for a grating of 50 nm pitch, exposed with the zone plate of Fig. 4 at the focal plane. (b) Modulation-transfer function (MTF) of the grating in (a) as a function of deviation from the focal distance of 19 μm.

CONCLUSION

We have developed a suite of general simulation tools for ZPAL and compared the results with patterns, exposed with UV ZPAL. The feasibility of transferring 25 nm features by X-ray ZPAL was also indicated. We plan to use these tools to facilitate the improvement our existing UV-ZPAL system and to design the optimal X-ray ZPAL system.

ACKNOWLEDGEMENTS

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