Zone-Plate-Array Lithography (ZPAL): Optical Maskless Lithography for Cost-Effective Patterning

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ABSTRACT
Zone-Plate-Array Lithography (ZPAL) is an optical-maskless-lithography technique, in which an array of tightly focused spots is formed on the surface of a substrate by means of an array of high-numerical-aperture zone plates. The substrate is scanned while an upstream spatial-light modulator, enabling “dot-matrix” style writing, modulates the light intensity in each spot. We have built a proof-of-concept system using an array of zone plates, and the Silicon Light Machines Grating Light Valve (GLV™) as the light modulator. We have demonstrated fully multiplexed writing, multilevel alignment and resolution corresponding to k1 < 0.3. This system currently operates at \( \lambda = 400 \text{nm} \) and utilizes well-known I-line processes. Diffractive optics such as zone plates offer significant advantages over refractive approaches since near-ideal performance is achieved on axis, reliable planar fabrication techniques are used, costs are low, and the approach can be readily scaled to shorter wavelengths. In this paper, we also developed models and analyzed the cost-of-ownership of maskless lithography (ZPAL) versus that for optical-projection lithography (OPL). In this context, we propose the use of an effective throughput to consider the photomask delivery times in the case of OPL. We believe that ZPAL has the potential to become the most practical and cost-effective method of maskless lithography, enabling circuit designers to fully exploit their creativity, unencumbered by the constraints of mask-based lithography. This may revolutionize custom circuit design as well as research in electronics, NEMS, microphotonics, nanomagnetics and nanoscale science and engineering.

Keywords: Lithography, maskless lithography, low-k1 lithography, zone-plate-array lithography, zone plates, cost-of-ownership.

1. INTRODUCTION

Lithography is the key enabling technology responsible for the proliferation of micro- and nano-scale integrated devices. Patterning via optical-projection lithography (OPL) remains the most expensive as well as one of the most complicated steps in the semiconductor manufacturing process. Patterns etched into a photomask are imaged by highly complex, refractive optical systems onto the surface of the photosensitive-coated wafer. The complexity of the optical system is further enhanced by the nanoscale tolerances required in the printed image, which translates into extremely tight tolerances on the allowable aberrations in the imaging optics. Progress (both technical and economic) in the semiconductor industry is primarily defined by the decrease in feature sizes. Smaller feature sizes are accompanied by even more stringent requirements on the performance of the optics as well as the entire OPL tool. In the past, reducing the exposure wavelength as well as clever designs of the photomask, and illumination systems traded off some of these complexities. Such resolution-enhancement techniques1 (RETs) shifted the complexities from the optics to the photomask and the illumination sub-systems of the OPL tool. Meanwhile, material issues constrained the path to shorter wavelengths as it became extremely difficult and expensive to design aberration-free optical systems for wavelengths below 193nm. This shifted even more complexity onto RETs and enhancements to the photomask such as optical-proximity correction (OPC). Manufacturing tolerances on the photomasks themselves became more stringent, driving up their costs exponentially. It is clear that increasingly clever (and hence, complex!) photomask patterns will be

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responsible for driving optical lithography to the limits of the lithographic process. Hence, it is a worthwhile exercise to consider alternative patterning techniques, which sidestep the requirement of expensive photomasks.

In the semiconductor industry OPL is very successful in large part because the photomask can be used repeatedly to pattern thousands of wafers at high yield and at high speeds. Although maskless lithography avoids the extra cost and delays involved in the photomask, it is usually very slow compared to OPL. Thus maskless lithography offers flexibility in patterning at the cost of speed. Several forms of maskless lithography have been proposed. In most proposals, patterns are recorded in a resist layer either by focused beams of photons, electrons or other charged particles, or by images projected from a reconfigurable photomask. In the former, proposals have been made to increase the number of focused beams in order to increase the writing speed. Since electrons as well as any charged particles are deflected by electric and magnetic fields, the position accuracy that can be achieved with electron-based lithographic systems is typically limited to over 10nm. Moreover, the process incompatibilities raised by using electrons instead of photons make it much more difficult to be accepted into a manufacturing process. In the latter proposal, complex projection optics are required. The nature of the complexity is shifted to a much larger demagnification factor (over 250X). This is due to the fact that individually addressable pixels on a MEMs-based reconfigurable photomask (spatial-light modulator) are typically large (of the order of 10 µm). This problem is slightly easier to solve if smaller image (so-called field) sizes are used. However, smaller field sizes severely deteriorate the writing speed. Although such maskless-optical-projection lithography (MOPL) could be compatible with existing OPL materials and processes, the cost and complexity involved in these systems will likely impede their general acceptance. Beyond the semiconductor industry, we believe that a simpler, low-cost technology for flexible lithography will be invaluable in enabling the nanotechnology revolution.

At MIT, we have developed a technique that uses a large number of focused optical beams writing in parallel. The large number of tightly focused beams is created by an array of high-numerical aperture diffractive lenses, of which zone plates are the simplest ones. Hence, this technology is called zone-plate-array lithography (ZPAL)\(^2\). Light in each focused spot is controlled by one pixel of an upstream spatial-light modulator. The wafer is scanned on a high-precision stage in the focal plane of the zone-plate array (ZPA), while the light in each spot is modulated. Thus, patterns of arbitrary geometry are written in a “dot-matrix” fashion. A simple schematic of ZPAL is shown in Figure 1.

![Figure 1: Schematic of Zone-Plate-Array Lithography (ZPAL). An array of high-numerical aperture zone plates create an array of tightly focused spots. The substrate is scanned while a spatial-light modulator controls the light in each spot. Patterns are printed in a “dot-matrix” fashion. Scanning-electron micrographs on the left show a portion of a zone-plate array and a single zone plate. These phase zone plates were designed to operate at \(\lambda = 400\text{nm} \) at \(\text{NA} = 0.7\). They were fabricated in fused silica using scanning-electron-beam lithography. The spatial-light modulator in our prototype system is the Grating Light Valve from Silicon Light Machines.](image-url)
Since two-level phase zone plates can be fabricated using planar techniques, we are able to manufacture arrays containing over 1000 zone plates readily (see Figure 1 inset)\textsuperscript{3}. Our fabrication techniques ensure the uniformity of all optical properties including the focal length across the array. In fact, we have verified this via measurements made on a large-area micromagnetic device\textsuperscript{3}. In addition, numerical apertures as high as 0.95 have been demonstrated in the past\textsuperscript{5}. Another advantage of using diffractive optics is the potential to improve the focused spot by wavefront engineering. We made progress in this direction by showing the first lithography results with high-numerical aperture photon sieves\textsuperscript{3}, which have the potential to pattern images with increased contrast. Finally, diffractive optics can be readily designed to operate at shorter wavelengths\textsuperscript{4}. Thus, ZPAL has an architecture that can be extended to the limits of lithography.

2. LITHOGRAPHY PERFORMANCE

ZPAL has demonstrated excellent lithographic performance based on several figures-of-merit. We have patterned a variety of micro and nano scale devices, and demonstrated the feasibility of this technology. In this section, we briefly summarize these lithographic capabilities.

2.1 Resolution

Resolution in optical lithography is given by:

\[
W_{\text{min}} = k_1 \frac{\lambda}{\text{NA}},
\]

where \(W_{\text{min}}\) is printable minimum feature size, \(\lambda\) is the exposing wavelength, \(\text{NA}\) is the numerical aperture, and \(k_1\) is proportionality constant. In OPL, use of \(k_1\) less than 0.4 is very difficult, especially for non-periodic patterns. ZPAL is an incoherent imaging system, which implies that periodic as well as non-periodic patterns may be printed at very low \(k_1\). Examples of periodic patterns (dense lines and spaces) are demonstrated in Figure 2. The smallest lines have a width of 135nm, which corresponds to a \(k_1\) of 0.287. An example of a non-periodic pattern (the seal of MIT) is shown on the right. The smallest feature on this dense, non-periodic pattern is about 140nm, which corresponds to a \(k_1\) of 0.298. Note also that the linewidth control (i.e., the change in the linewidth) as small as 5nm is demonstrated in the dense gratings. In fact, with an exposure grid of 75nm and an 8-bit gray-level exposure scheme, this linewidth control can be theoretically 0.29nm! Of course, then the linewidth is limited by errors in the scanning stage, which themselves can be minimized to a few nanometers by using laser-interferometer control.

Figure 2: Resolution of ZPAL. Scanning-electron micrographs of periodic patterns (a) and a non-periodic pattern (b) in photoresist are shown. These were patterned at \(\lambda = 400\text{nm}\) and \(\text{NA} = 0.85\). These demonstrate that ZPAL is capable of printing \(k_1 < 0.3\) for patterns of any geometry. Note that (b) shows the seal of MIT.
2.2 Image contrast

In ZPAL, the first-order focused spot is used for lithography. The first-order focusing efficiency of phase zone plates is at most about 40%. This is slightly misleading as the remaining 60% of the light is distributed in the focal plane in such a manner that the aerial power density is extremely low compared to the first order of diffraction. As demonstrated by our results below, the effect of this background appears to be less than deleterious effects due to flare in OPL. Figure 3 (a) shows a scanning-electron micrograph of dense lines and spaces of width 290nm spanning an area of over 10mm². This pattern was printed with over 1000 zone plates in the presence of all the background in the focal plane. In spite of the 60% background from each zone plate, the lines were resolved very uniformly across the entire pattern. This is possible as the background energy is spread over extremely large areas compared to the main 1st order lobe. One can employ gray-scale optimization techniques to further overcome the effects of this background. This is demonstrated in a “worst-case” scenario shown in Figure 3(b), where a single spot is left unexposed in the center of a completely exposed square. By appropriate gray-scale modulation, the single unexposed spot can be resolved as shown. Note that there are almost 5000 exposed pixels surrounding this one unexposed pixel in this case!

Figure 3: Issue of contrast in ZPAL. (a) Scanning-electron micrographs of 290 lines and spaces covering an area of over 10mm². This was patterned by over 1000 zone plates at λ = 400nm and NA = 0.7. Each white square shown in the top SEM represents the portion of the pattern printed by one zone plate. (b) Scanning-electron micrographs of a single unexposed spot in the center of a large exposed square. This was printed at λ = 400nm and NA = 0.85.

2.3 Pattern fidelity

We have also demonstrated various metrics of pattern fidelity using ZPAL. Using a combination of sub-pixel printing and gray-scale modulation, we have developed efficient algorithms to determine the optimum exposure dose map for any given pattern. Although these algorithms are general to any incoherent imaging system, we have applied these to ZPAL and the optimized results are demonstrated in Figure 4. This pattern-optimization technique is capable of improving line-edge shortening, linewidth uniformity, corner- rounding, placement errors, and overall process latitude. This can also be used to almost perfectly emulate the optical characteristics of an OPL tool, thereby allowing seamless insertion of ZPAL into the process flow. Pattern-placement error of less than 30nm was demonstrated by simple calibration of our system³. We also developed unique alignment techniques⁹, which have the potential to achieve sub-10nm alignment accuracy in the future¹⁰.
3. COST-OF-OWNERSHIP

Beyond the intricate technical issues, which transform a lithographic technology into a high-yield manufacturable process, the economic issues often are almost equally important. The cost-of-ownership analysis is a tool that can assist in estimating the true cost of a lithographic technology irrespective of the technical details. Thus, it is a valuable tool to compare the myriad technologies for next-generation lithography. Here, we compare the cost of ZPAL to OPL using scanners or steppers.

The cost-of-ownership for lithography\textsuperscript{11, 12} is defined in terms of dollars per wafer-level\textsuperscript{13} and it is expressed as

\[
CoO = P_w + \frac{M_0}{M_u} + \frac{E_0 + D \times E_M}{D \times T \times U \times 365 \times 24},
\]

(2)

where \(P_w\) is the process cost per wafer level, \(M_0\) is the photomask cost, \(M_u\) is the photomask usage in number of wafer-levels exposed per photomask, \(E_0\) is the lithography equipment cost, \(D\) is the depreciation time in years, \(E_M\) is the lithography equipment maintenance cost per year, \(T\) is the throughput in wafer-levels per hour (WPH), and \(U\) is the lithography equipment utilization level.

3.1 Effective throughput

In conventional CoO analyses of OPL, the throughput used in equation (2) is the raw writing speed of the lithography equipment. We would like to modify this slightly by taking into account the actual time between completion of layout design and the end of the life of the mask, thereby taking into account the mask delivery time, \(M_d\). Thus, the effective throughput is defined as:

\[
T_{\text{eff}} = \frac{1}{\frac{1}{TU} + \frac{M_d}{M_u}}
\]

(3)

Figure 5 shows a plot of \(T_{\text{eff}}\) as a function of \(M_d\) and \(M_u\) for \(T = 100\)WPH and \(U = 70\%\). For a mask delivery time of 1 week, the effective throughput is \(\sim 30\) WPH for a mask usage as high as 10,000. For lower mask usages and higher
mask delivery times, the effective throughput is correspondingly smaller. Thus, it is obvious that the mask delivery time has a significant impact on the “true” throughput of the lithographic technology especially for low-mask-usage levels. Therefore, we replace $TU$ in equation (2) with $T_{eff}$ in the subsequent analysis.

![Figure 5: Effective Throughput as a function of mask usage and mask delivery time. We assumed a raw throughput of 100 wafer-levels/hr and utilization of 70%.

3.2 Break-even mask usage

As its name implies, maskless lithography removes the photomask from the manufacturing process. Therefore, the CoO for maskless lithography can be rewritten as

$$CoO_{\text{ML}} = P_{W_{\text{ML}}} + \frac{E_{0_{\text{ML}}} + D_{\text{ML}} \times E_{M_{\text{ML}}}}{D_{\text{ML}} \times T_{\text{ML}} \times U_{\text{ML}} \times 365 \times 24}, \quad (4)$$

where the subscript ML refers to maskless lithography. We can define the break-even mask usage, $\langle M_u \rangle$ as that value of mask usage where the CoO of OPL and maskless lithography are equal. By comparing equations (2) and (4), and using equation (3), we can derive an expression for $\langle M_u \rangle$.

$$\langle M_u \rangle = \frac{M_0 + M_d \left[ \frac{E_0 + DE_M}{D(365)(24)} \right]}{D_{\text{ML}} T_{\text{ML}} U_{\text{ML}}(365)(24) - \frac{E_0 + DE_M}{DTU(365)(24)}} \quad (5)$$

Here, we assumed that $P_{W_{\text{ML}}} = P_w$, which is reasonable since the maskless technology is assumed to employ the same illumination wavelength as OPL. From equation (5), we can estimate the largest mask usage that justifies the use of maskless lithography over OPL in terms of CoO.

3.3 Discussion

In this section, we analyze the effect of various parameters on the cost-effectiveness of maskless lithography as compared to OPL. The primary quantifying metric is the break-even mask usage.
Figure 6 shows the break-even mask usage as a function of the OPL tool cost. The assumptions used in the calculation are enumerated in the figure caption. Note that for typical values, the break-even mask usage is over a thousand wafers per mask even at low tool costs of ~ $10M. For a high tool cost of $50M, the break-even mask usage is as high as 3500 i.e. it is cheaper to use maskless lithography if fewer than 3500 wafers are printed using one photomask.

![Figure 6: Break-even mask usage as a function of OPL tool cost. We assumed that M₀ = $25,000, M₄ = 1 week, D = 5 years, E₄ = $1M, T = 100WPH, U = 70%, E₄ML = $8M, E₄MML = $1M, and T₄ML = 5WPH.](image)

Figure 7 shows the break-even mask usage as a function of the photomask cost. The assumptions are defined in the caption. Note that for a typical mask of cost $25,000, maskless lithography is cheaper if fewer than ~1800 wafers are printed per mask. This number increases linearly with increasing mask cost.

![Figure 7: Break-even mask usage as a function of photomask cost. We assumed that E₀ = $25M, M₄ = 1 week, D = 5 years, E₄ = $1M, T = 100WPH, U = 70%, E₄ML = $8M, E₄MML = $1M, and T₄ML = 5WPH.](image)

Figure 8 shows the break-even mask usage as a function of the mask delivery time (in weeks). For a typical delivery time of 1 week, the break-even point is around 1800 wafers per mask. The break-even point is almost linearly proportional to the mask delivery time.

![Figure 8: Break-even mask usage as a function of photomask cost. We assumed that E₀ = $25M, M₄ = 1 week, D = 5 years, E₄ = $1M, T = 100WPH, U = 70%, E₄ML = $8M, E₄MML = $1M, and T₄ML = 5WPH.](image)
Figure 8: Break-even mask usage as a function of photomask delivery time. We assumed that $E_0 = 25M, M_0 = 25,000, D = 5$ years, $E_M = 1M, T = 100WPH, U = 70\%, E_{OPL} = 8M, E_{MML} = 1M$, and $T_{ML} = 5WPH$.

Figure 9 shows the break-even mask usage as a function of the raw OPL tool throughput in wafers per hour (WPH). As expected, higher the throughput, the smaller the break-even point. Even at very high throughputs of 200 WPH, the break-even point is over 1750 wafers per mask.

Figure 9: Break-even mask usage as a function of OPL tool throughput. We assumed that $E_0 = 25M, M_0 = 25,000, D = 5$ years, $E_M = 1M, M_d = 1$ week, $U = 70\%, E_{OPL} = 8M, E_{MML} = 1M$, and $T_{ML} = 5WPH$.

We can also compare the actual CoO of maskless lithography and OPL as a function of the mask usage. In Figure 10, difference in CoO between OPL and maskless lithography (defined as the savings achieved by using maskless lithography) is plotted as a function of the mask usage. As expected, for low mask usage, the savings are very high. Even for a mask usage of 1000, the savings achieved by maskless lithography is about $65 per wafer-level.
Figure 10: Difference in CoO between OPL and maskless lithography as a function of mask usage. We assumed that $P_W = 7$, $E_0 = 25M$, $T = 100$ WPH, $M_0 = 25,000$, $D = 5$ years, $E_M = 1M$, $M_d = 1$ week, $U = 70\%$, $E_{OML} = 8M$, $E_{MML} = 1M$, and $T_{ML} = 5$ WPH.

Figure 11 shows the CoO of maskless lithography as a function of its raw throughput. This analysis creates a compelling case to pursue the highest possible throughput in maskless lithography. CoO is over $4000$ in the case of very slow maskless lithography ($T \sim 0.1$ WPH) such as in single-beam scanning-electron beam lithography (SEBL). ZPAL can achieve throughputs in the order of 5 WPH, which reduces the CoO to about $90$, a reduction of over an order of magnitude compared to SEBL.

![Figure 11: CoO of maskless lithography as a function of throughput. We assumed that $P_W = 7$, $D = 5$ years, $U = 70\%$, $E_{OML} = 8M$, and $E_{MML} = 1M$.](image)

4. CONCLUSION

The feasibility of maskless lithography in the form of ZPAL was demonstrated in the past. In this paper, we summarize the earlier results as well as present some improved results in terms of resolution, image contrast and pattern fidelity. ZPAL has shown high quality patterning at extremely low $k_1$ values (less than 0.3). We also analyzed the cost-of-ownership of ZPAL and compared it to that of OPL. We demonstrated that the mask delivery time could have a significant impact on the CoO especially for low mask usage. Hence, we propose the use of an “effective throughput” for OPL, which takes into account the mask delivery time. Finally, our analysis indicates that for a typical case, maskless lithography is justified when the mask usage is fewer than ~1800 wafers per photomask.
REFERENCES


