

Limits on Resolution and Possibilities for Optimized Imaging of EUV Lithography in Connection with Advanced AI Chips

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Abstract—Advancements in generative artificial intelligence and high-performance computing are driving improvements in logic chips, particularly in transistor density, interconnect bandwidth, and power efficiency, with critical layer patterning under 10 nm. Extreme ultraviolet (EUV) lithography employs a 13.5 nm wavelength and reflective projection, reducing the dependence on multiple patterning techniques used in 193 nm immersion lithography. The paper reviews known data and relates various parameters, using Rayleigh relations to estimate the imaging capacities of 0.33 NA and 0.55 NA systems. It also treats such matters as depth of field reduction, half-field of view, mask shading, and overlay control with regard to high NA conditions. The results indicate that 0.55 NA helps to raise the single-exposure resolution—from about 13 nm to roughly 8 nm—yet the yield of sub-10 nm patterns becomes increasingly unreliable because of photon shot noise, material dispersion, or local defects. Thus, when optimizing lithography for advanced AI chips one must not merely aim at minimal linewidths but also at a balance of resolution, dose, depth of field and defect rate.

Keywords—extreme ultraviolet lithography, High numerical aperture, Resolution limit, Random phenomena, AI chip manufacturing

I. INTRODUCTION

The latest AI chips depend upon massive parallelism, fast interconnects within the chip, and high-bandwidth memory. To improve power efficiency, it is necessary to increase transistor density and minimize interconnect lengths. Photolithography conveys the layout into the wafer form, and this step has a direct bearing on the feature size, positional error, and manufacturing cost. 193 nm immersion deep ultraviolet lithography now reaches some of the more advanced nodes thanks to off-axis illumination, to phase-shifting masks, to optical proximity correction, or to multiple patterning—yet longer exposure times will themselves add to overlay error and slow down the whole process. Early studies treated EUV as a key technical possibility for going beyond the 193 nm lithography limit [1]. At present, EUV lithography operating at 13.5 nm is applied to essential layers of logic and memory, as well as to mass-scale 7 nm, 5 nm, and 3 nm processes [2, 3].

Earlier studies of EUV have treated light sources, mirrors, multilayer masks, photoresists, and computational lithography. For single-exposure systems of the 0.33 NA type the resolution is roughly 13 nm, whereas the 0.55 NA high numerical aperture variety targets about 8 nm—a value that may help to cut down multiple exposures [4]. Yet the progress of NA need not be considered merely as a performance win: the depth of field will shrink,

the incident angle is going to be higher, and the three-dimensional character of the mask becomes clearer. At the

same time, the actual count of photons per unit dose of EUV is not unlimited, so tiny features suffer more from shot noise or from material dispersion [5-7]. Thus, the problem has changed from “whether the pattern can be printed” to “whether the pattern can be printed stably with a sufficiently low defect rate”.

This paper analyzes the resolution limits of EUV, the distinctions between 0.33 NA and 0.55 NA setups, the causes of random defects, and possible routes to optimization. This study lays a solid foundation for thinking about the engineering trade-offs of advanced AI chip graphics.

II. IMAGING BASICS AS WELL AS RESOLUTION LIMITS OF EUV LITHOGRAPHY

A. Wavelength, Numerical Aperture, and Process Factor

The critical size for projection lithography is normally associated with the Rayleigh relation, which gives CD as the printable critical size, λ as the exposure wavelength, NA as the numerical aperture, and k_1 as a process factor combining—in an overall sense—the illumination characteristics, mask layout, photoresist quality and capacity for computational correction [8].

$$CD = k_1 \lambda / NA \quad (1)$$

With regard to equation (1), resolution improves if the wavelength is shorter, if the NA is larger, or if k_1 is smaller. EUV brings about a reduction of the wavelength—from 193 nm down to 13.5 nm—with small pattern sizes even at low NA. With $k_1 \approx 0.32$, the CD of the 0.33 NA setup is about 13.1 nm, while that of the 0.55 NA case comes to roughly 7.9 nm (values similar to those of the currently marketed) about 13 nm and 8 nm [3, 4]. However, k_1 is not subject to continuous reduction. When the imaging limit is approached, the aerial image becomes sensitive to focal length errors, mask imperfections, and resist noise—resulting in a narrowing of the process window. Such an estimate calls for caution in assuming that nominal resolution ensures trouble-free printing of every pattern. Dense or isolated line features, as well as contact holes, have various diffraction behaviors. Each may require special illumination or mask design, with consequent differences in the process window.

B. Depth of Field and Focal Length Budget

Depth of field can be approximated as:

$$DOF = k_2 \lambda / NA^2 \quad (2)$$

In Eq. (2), the depth of field turns out to be inversely

proportional to the square of the photoresist (NA). If the NA is taken up from 0.33 to 0.55, then the depth of field is roughly $(0.33/0.55)^2 \approx 0.36$, with all else kept constant. From this it follows that high-NA systems depend heavily upon wafer flatness, upon resist thickness control, upon plateau height correction, and upon aberration compensation.

High-performance AI chips make use of intricate structures and of multiple interconnect layers, and their surfaces are not flat. Theoretical resolution translates into real yield only if accurate focusing and flattening are achieved. With regard to actual manufacturing conditions, the focal length budget needs to account for wafer warpage, film thickness fluctuation, plateau consistency, and thermal drift of the lens—this leaves little room for the photoresist itself. This is why high NA methods now favor thin resist layers and dense sampling of the focus area.

C. Reflection Optics and Three-Dimensional Masking Phenomena

EUV is very strongly absorbed by nearly all substances, which rules out the use of normal transmission lenses and forces reliance on multilayer mirrors in vacuum. Light loses energy progressively along the collecting mirror, along the illumination path, at the mask, and at the projection mirror, the actual light dose to the wafer is determined by the full reflection efficiency of the optics. Higher light-source power brings about greater throughput but may also cause excessive heat, dirt, or shorter lifetimes for optical parts.

EUV masks are composed of a number of thin reflective films plus absorbers of given thickness. With inclined incidence one finds not only shadows but also phase differences and asymmetric diffraction in the absorber—this is the 3D mask effect. The larger the NA, the stronger are the directional errors (in the sense of misalignment), possibly giving rise to wrong sizes or poor alignment or low contrast [9]. Practical correction benefits from thinner absorbers, good mask geometry, and precise electromagnetic modeling.

III. A COMPARISON OF PERFORMANCE FOR THE 0.33 AND 0.55 NA PLATFORMS

A. Resolution—Exposure—Field of View

The magnitudes given are not absolute, the actual printable size still depends upon the pattern, on illumination, on dose, and on possible etching errors. As shown in Table 1, the typical single-exposure resolution improves from approximately 36 – 40 nm for 193 nm immersion DUV to about 13 nm for 0.33 NA EUV and 8 nm for 0.55 NA high-NA EUV, although these improvements introduce additional challenges, including stochastic defects, mask 3D effects, and reduced depth of field.

Table 1. Comparison of advanced optical lithography platforms

Parameter	193 nm immersion DUV	0.33 NA EUV	0.55 NA High - NA EUV
Wavelength	193 nm	13.5 nm	13.5 nm
Numerical aperture	up to 1.35	0.33	0.55
Typical single - exposure resolution	approximately 36–40 nm	about 13 nm	about 8 nm

Optical element	refractive lens	reflective mirrors	anamorphic reflective mirrors
Main scaling issue	multi - patterning and overlay	stochastics and mask 3D	reduced DOF, half field and mask 3D
Primary optimization	Multiple patterning+OPC	source-mask-resist co-optimization	full ecosystem co-optimization

High-NA systems are based on deformable projection optics with varying scaling ratios, allowing big mirrors without new mask dimensions. There is a trade-off: the field of view per exposure comes to roughly half the size of the usual EUV [10]. When designing AI accelerators, attention must be given to layout and stitching errors, which should be integrated during the design technology co-optimization phase. While layout partitioning in regular computing arrays is manageable, interconnects across fields complicate the design due to functional dependencies. Small-chip packaging helps to avoid extreme exposure problems for one very large chip, though it moves certain difficulties to the packaging or interconnect level. Among the most direct benefits of high-NA are better imaging contrasts and less need for double patterning in key layers. Although fewer exposures or etch steps help to keep overlay error low and to shorten process cycles, all of the following items—scanners, masks, resists, metrology, and inspection—need updating. A purely optical improvement does not guarantee a useful yield unless supporting technologies meet their own standards.

B. Trade-offs between Resolution, Dose, and Throughput

EUV dose is generally given in units of mJ/cm². With higher doses one may expect more absorbed photons, less relative shot noise, and more regular local critical sizes—but exposure time rises and the overall throughput falls as well. A very low dose is beneficial for throughput, yet it carries a significant risk of missing holes, broken lines, or poor line-edge smoothness. Such contradictions are frequently referred to as the resolution-line edge roughness-sensitivity triangle, and all three properties cannot be simultaneously optimized [6, 11]. Nominal resolution can be improved by shrinking pattern dimensions or lowering dose to raise productivity, but stochastic failure risks cannot be removed in this way. It is therefore better to evaluate the yield of good chips per unit cost rather than to focus solely on the minimal linewidth. For large-area AI chips, one open interconnect or missing contact hole is one cause of full-scale chip failure, low-probability defects must not be dismissed. With regard to yield, an average metric is no guarantee that the risk has been eliminated. Even if only a tiny fraction of a given kind of contact hole is not fully open, the effect might not be easily seen with small test patterns, yet—when such structures occur repeatedly in huge numbers over the whole chip—the chance of failure is greatly increased.

IV. RANDOM EFFECTS FOR SUB-10 NM IMAGING

A. Photon Shot Noise and the Discreteness of Matter

EUV single-photon energy is about 92 eV, higher than that of 193 nm photons. With identical energy doses, EUV implies a smaller total count of incoming photons, with absorption processes clearly marked by discrete statistics. If the available local photon number is too small, both

photoacid formation and secondary electrons vary, and this variation tends to affect the regularity of edges, of linewidths, and of contact holes. Smaller patterns contain fewer effective photons and fewer resist molecules, so relative fluctuations are more marked [5, 6].

Chemically amplified photoresists employ one photon to start a multi-step reaction with an eye toward improved sensitivity, yet acid diffusion may lead to blurred boundaries, and uneven distributions of reagents or quenchers create fluctuations. Among metal oxide photoresists there is strong EUV absorption and small molecule size, which seem to allow high-NA resolution, though sensitivity, surface roughness, etchability, and compatibility remain to be

be considered [11, 12]. Such random problems are not just simple optical aberrations and need more than OPC for elimination. Even the baking or development steps following exposure can have an effect on acid diffusion and on dissolution contrast. Too much diffusion tends to remove certain irregularities yet to blur nearby features, too little leads to partial or incomplete reactions. Therefore, one has to match the choice of materials with the actual pattern and process window.

B. Local Defects and Large Chip Yield

Systematic imaging errors can usually be corrected through adjustments in focal length, dose, or mask, while random flaws are infrequent and not localized. With chip area denoted as A and defect density per unit area taken as D_0 , it is possible to estimate roughly the defect-free yield by means of a simplified Poisson model:

$$Y \approx \exp(-A \cdot D_0) \quad (3)$$

Eq. (3) indicates that, under the same defect density, larger AI accelerators are more likely to suffer from reduced yield. Thus, process development needs not only to lower the typical CD deviation, but also to avoid isolated local failures, to apply high-sensitivity methods, to sample statistically and to consider layout hotspots or design redundancy. Assessment of extreme σ tail events cannot be fully captured by an average of line edge roughness—a full chip model is better suited to such analysis [7].

V. SYSTEM-LEVEL OPTIMIZATION OF IMAGING PERFORMANCE

Control of wafer-level photon flux is basic to achieving a balance between randomness and throughput. Laser-plasma setups employ high-power lasers for tin-droplet agitation, yielding 13.5 nm light. Important developments pertain to hit rates of droplets, conversion efficiency, debris suppression, mirror contamination, and pulse stability. The source's power is not something that can be studied separately, it has to be analyzed together with the required photoresist dosage plus equipment maintenance costs. The illumination pupil can be adjusted for various pattern types, and optimizing source and mask together improves image log slope and exposure-focus tolerance. At high photon densities, polarization, non-centrocentric effects, and orientation-dependent masking must be considered.

Optimization of a mask involves considerations of multilayer film reflectivity, absorber thickness, wall angles,

line edge roughness, and defect control. Reducing absorber thickness can minimize shading but may complicate processing. For high photosensitive areas, reliance on thin-mask estimates is inadequate, exact electromagnetic field data is essential, and various orientations should be analyzed separately. Computational lithography makes use of OPC, reverse lithography, source mask optimization, and hotspot prediction. It is possible to pre-correct systematic errors in the mask but not to foresee exactly what will happen in each exposure. A more practical strategy is to couple deterministic optical models with stochastic photoresist models, to raise the local dose for risky configurations, or to change auxiliary features or design rules accordingly. Key photoresist properties include absorption, quantum efficiency, and film thickness. Thin resist layers help to get a large NA depth of field or to avoid pattern collapse, yet they may not survive immediately after etching, so they usually call for high selectivity substrates or for multilayer transfer techniques.

Metrology challenges in CD-SEM measurement involve noise blending with roughness, potentially addressed via scattering data or statistical denoising. Exposure, development, etching and inspection must be studied as a single continuous process, since an excellent aerial image need not yield a good silicon pattern. Among recent publications there is evidence that high NA patterning is feasible only if ecological relationships along with etching and metrology are verified [13].

VI. CONCLUSION

The article discusses the resolution limits of EUV lithography, emphasizing 13.5 nm wavelength for high resolution and the role of Numerical Aperture (NA). A configuration with 0.33 NA yields 13 nm resolution, while 0.55 NA could reach 8 nm, potentially reducing multiple patterning needs. However, increasing NA decreases depth of field, causing challenges related to mask effects and focal length control. Factors like photon numbers and chemical irregularities can result in defects that critically impact yield in complex AI chip manufacturing. Optimizing production requires coordination among various technologies, with high-NA EUV seen as vital for achieving superior resolution. Future improvements will focus on light source stability, better photoresists, and integration among design and processes.

The present work is a review rather than a report based on wafer-scale experiments under uniform equipment and process conditions, it is possible to go beyond it by means of published data or of simulation to analyze quantitatively the dose-focal length windows, NILS, LWR, and defect rates. Generally speaking, high-NA EUV is a key factor in pushing forward with the scaling of advanced AI chips, though mass use calls for a well-balanced yield, speed, cost, and technology state.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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