

Research on Fundamental Principles and Performance Optimization Strategies in Lithography Technology

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Abstract. This paper provides a comprehensive review of recent advances in lithography technologies, focusing on Deep Ultraviolet (DUV), Extreme Ultraviolet (EUV), and Nanoimprint Lithography (NIL). This work synthesizes findings from existing studies to highlight the fundamental principles, performance characteristics, and practical challenges of each method. The comparison centers on key metrics, including resolution, depth of focus, exposure dose, line-edge roughness, overlay accuracy, and throughput, revealing how different approaches balance these competing factors. DUV lithography offers process maturity and cost efficiency but relies on multiple patterning to extend scaling. EUV provides higher intrinsic resolution, though it is constrained by source power, resist sensitivity, and stochastic variation. NIL demonstrates excellent resolution potential and process simplicity, yet defect control and alignment remain critical barriers for large-scale deployment. By consolidating insights across optical, material, and metrology domains, this review clarifies the trade-offs that shape manufacturability and points to opportunities for hybrid solutions, material innovation, and sustainable process design. The analysis concludes with perspectives on how coordinated progress in optics, resists, and alignment strategies can enable continued semiconductor scaling.

Keywords: deep ultraviolet lithography, extreme ultraviolet lithography, nanoimprint lithography, line-edge roughness, overlay control

1. Introduction

Lithography remains the rate-limiting step at advanced nodes because imaging physics, resist chemistry, and precision mechanics jointly determine what can be printed repeatably in high-volume manufacturing (HVM). On the optical side, progress has historically followed wavelength and numerical aperture (NA): dry and immersion DUV at 248/193 nm extended Rayleigh scaling but compressed depth of focus (DOF), narrowing process latitude as NA increased [1-3]. EUV at 13.5 nm resets intrinsic resolution yet introduces system constraints—reflective optics in vacuum, source-limited throughput, and tighter tolerances that couple overlay and CDU to thermal control and stage dynamics, especially for high-NA architectures [4,5]. In parallel, NIL promises single-shot, template-based replication, but logic-grade deployment is still bounded by large-area uniformity, defectivity, template durability, and alignment control [4].

Materials are equally decisive. Positive-tone chemically amplified resists (CARs) balance sensitivity against blur and line-edge roughness (LER) through photoacid generation, diffusion, and development kinetics [6]. Inorganic/metal-oxide (MOx) strategies raise EUV absorption and network density, shifting the dose–LER frontier and improving etch resistance [7-9]. Yet stochastic variation at EUV scales penalizes throughput because reducing LER typically requires a higher absorbed dose, while usable wafers-per-hour (WPH) ultimately scales with source power relative to that required dose [4,5,10,11]. Meanwhile, multilayer overlay budgets continue to tighten; moiré-fringe alignment provides high sensitivity and useful capture range across optical and imprint platforms, with NIL-specific advances in dual-frequency measurement and robust phase extraction enabling faster in-situ alignment [12-14].

Much of the literature treats these axes in isolation—optics and integration for EUV [4,5], resist chemistry for sensitivity/LER [6-9], or metrology/alignment for overlay [12-14]. What is less consolidated is a comparative, parameter-centric view that links resolution, dose, LER, overlay, and throughput across DUV, EUV, and NIL, and maps those links onto HVM economics (WPH and cost of ownership).

In advanced lithography processes, several key coupled challenges critically impact manufacturability: (1) The resolution-throughput trade-off, where pushing resolution through higher NA or shorter wavelengths in DUV shrinks process windows and drives multi-patterning with overlay penalties, while EUV's gains remain bottlenecked by source power limitations [2,4,5,11,15]. (2) The dose-LER compromise, in which photon shot noise and reaction–diffusion blur dominate roughness at EUV scales; chemically amplified resists rely on tuning photoacid generator and quencher chemistry alongside bake kinetics, whereas inorganic or metal-oxide approaches exploit higher absorption and denser networks to deliver comparable fidelity at lower doses [6-10]. (3) The overlay-latitude control challenge, as higher NA reduces depth of focus and heightens sensitivity to thermal and vibrational effects, making precise multilayer alignment dependent on advanced metrology and fast feedback loops, with moiré-based techniques providing both precision and capture range, including adaptations for NIL platforms [2,12-14].

In advanced lithography processes, three major factors are particularly important for manufacturable performance. Firstly, connecting optical scaling, resist chemistry, and metrology to system-level outcomes shows how numerical aperture, wavelength, and exposure dose propagate to depth of focus, line-edge roughness, overlay accuracy, and ultimately throughput for DUV, EUV, and NIL [2,3,10]. Secondly, practical levers can be identified for different technology nodes: in EUV, combining resist-side dose reduction with credible LPP power and stability improvements; in DUV, determining layers where multiple patterning remains cost-effective; and in NIL, defining the conditions under which alignment precision and defect control enable effective throughput [2,4,5,11]. Thirdly, integration and sustainability emerge as critical constraints, since exposure count, required dose, and metrology overhead directly relate to fab-level economics and energy consumption. In this context, materials innovations such as metal-oxide resists or advances in moiré-based alignment can provide disproportionate gains in throughput and cost of ownership [4,9,11].

The overall significance lies in providing practical guidance: by treating resolution, dose, and overlay as a coupled system rather than isolated optimizations, the analysis supports evidence-based choices of lithography platform, resist class, and alignment strategy for advanced semiconductor manufacturing [4,5,7-9].

This work synthesizes insights on resolution, dose, overlay, and throughput, and offers a comprehensive comparative framework for evaluating DUV, EUV, and NIL lithography in the context of high-volume semiconductor manufacturing.

2. Fundamental principles of lithography

Modern photolithography integrates optical imaging, precision mechanics, and material chemistry to transfer nanoscale patterns from mask to substrate. While projection optics define the theoretical resolution, the chemical behavior of photoresists determines whether this limit can be realized in manufacturing. Photon absorption, photoacid generation, acid diffusion, and polymer modification collectively influence resolution, LER, and sensitivity [6-9]. Advances in both resist chemistry and optical system design are essential for continued scaling. For instance, inorganic photoacid generators (PAGs) such as ZrO_2 and HfO_2 clusters offer higher EUV absorption and faster proton release than organic PAGs, enabling sub-10 nm patterning while reducing stochastic defects [7-9]. This section first discusses photoresist photochemistry, then optical imaging and resolution fundamentals, and finally key performance features.

2.1. Photochemistry of photoresists

Photoresists are light-sensitive polymers whose solubility in a developer changes upon exposure. In chemically amplified resists (CARs), a small number of absorbed photons can initiate acid-catalyzed reactions, enabling high sensitivity through chemical amplification [6]. However, the same amplification process can introduce stochastic effects that manifest as LER—a critical factor in nanoscale patterning [6]. Acid diffusion during the post-exposure bake (PEB) process defines the spatial sharpness of the reaction front, directly linking photochemistry to pattern fidelity [7,8]. Both positive-tone and negative-tone CARs have been developed, each with distinct advantages and limitations in advanced lithography nodes [6].

2.1.1. Positive and negative photoresists

In positive-tone CARs, PAG-generated protons cleave acid-labile protecting groups on the polymer backbone, increasing solubility in the exposed regions so that they are removed during development. Hassaan demonstrated that optimization of the polymer matrix and PAG concentration can enhance both resolution and sensitivity by approximately 20% while maintaining low LER [6].

In contrast, negative-tone CARs rely on acid-catalyzed cross-linking. During PEB, the generated acid diffuses into unexposed areas, triggering polymer network formation and rendering those regions insoluble. This mechanism improves etch resistance but can reduce process latitude due to the difficulty of controlling the cross-linking extent [6].

From a process integration perspective, selecting between positive- and negative-tone resists requires balancing target resolution, etch selectivity, and compatibility with other lithography modules.

2.1.2. Photoacid generators and diffusion effects

PAGs serve as the initiators of chemical amplification, converting absorbed photons into strong acids. Their performance depends on the optical absorption cross-section at the exposure wavelength and the quantum yield of acid generation. Luo reviewed recent advances in inorganic PAGs, noting that materials such as ZrO_2 and HfO_2 clusters exhibit higher EUV absorption and faster proton release compared to organic sulfonium salts, enabling sub-10 nm patterning [8].

Acid diffusion length during PEB critically impacts image fidelity: longer diffusion lengths can improve process latitude but risk blurring edges and increasing LER. Kang reported that metal-oxide

PAGs can achieve high acid yield while intrinsically restricting diffusion, thereby enhancing both resolution and LER performance [9].

Beyond the intrinsic properties of PAGs, processing strategies can further control diffusion. Hasan described the integration of vapor phase infiltration (VPI) with lithography as a method to embed metal-oxide networks within the resist [7]. As shown in Figure 1, VPI can be performed post-lithography to strengthen patterned features or pre-lithography to pre-modify the resist. In the latter approach, alternating exposures to trimethylaluminum (TMA) and water vapor form a metal-oxide network in the polymer matrix, enhancing mechanical rigidity, increasing EUV absorption, and limiting acid diffusion—all contributing to improved resolution and reduced LER [7].

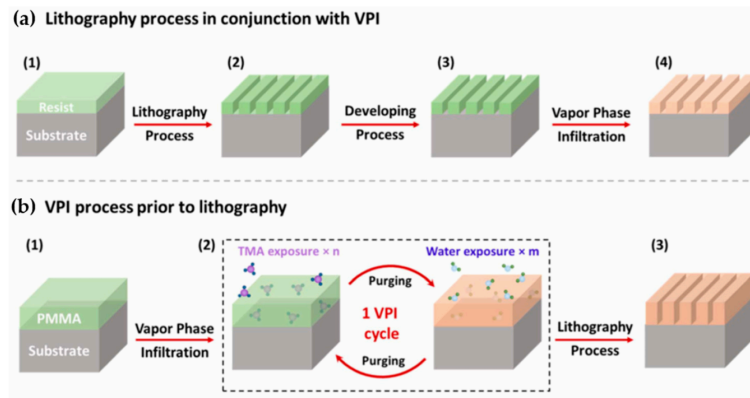


Figure 1. Two approaches for integrating vapor phase infiltration (VPI) with lithography: (a) post-lithography VPI to reinforce patterned features; (b) pre-lithography VPI to incorporate metal-oxide networks into the resist via alternating TMA and water exposures [7]

2.2. Optical imaging and resolution fundamentals

While the photochemistry of resists determines material response, the final pattern fidelity is equally constrained by the optical system's resolution and depth of focus (DOF). These parameters, governed by wavelength (λ), numerical aperture (NA), and process factors, define the physical limits within which resist chemistry operates [1,2]. High-NA immersion lithography has enabled sub-40 nm features but at the cost of reduced DOF, narrowing the process window and requiring precise focus control in conjunction with optimized resist formulations [2].

2.2.1. Diffraction limit and Rayleigh criterion

The resolution of a projection system is described by the Rayleigh criterion [1]:

$$CD = k_1 \frac{\lambda}{NA} = k_1 \frac{\lambda}{n \sin \theta} \quad (1)$$

where k_1 reflects resist performance, illumination, and mask design. As shown in Figure 2(a), lower NA improves resolution [2], but shorter wavelengths require new resist chemistries, and higher NA increases aberrations while reducing DOF [1]. Lithography has evolved from g-line (436 nm) to EUV (13.5 nm), with immersion techniques extending 193 nm ArF systems [1]. Optical improvements, phase-shift masks, off-axis illumination, and multiple patterning are often paired with advanced resists to maintain low- k_1 imaging [1,6]. At current technology nodes, optical scaling

alone approaches physical limits, placing greater emphasis on resist engineering to achieve high resolution without excessive optical complexity [1,6].

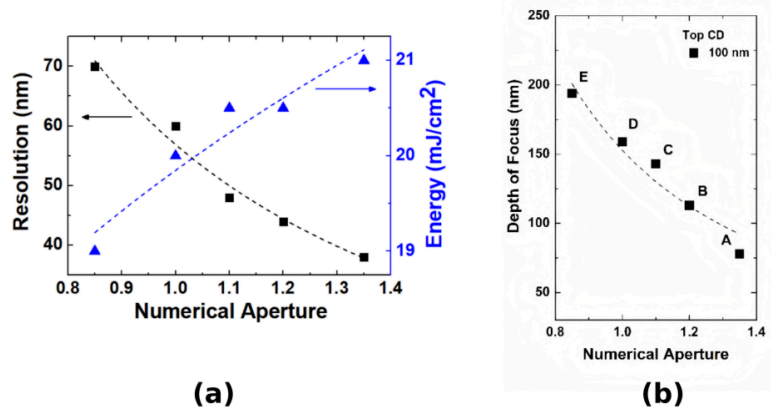


Figure 2. (a) Resolution and optimized exposure energy as a function of NA in ArF immersion lithography; (b) Depth of focus as a function of NA for 100 nm line/space features in ArF immersion lithography [2]

2.2.2. Numerical aperture and depth of focus

The DOF is given by [2]:

$$\text{DOF} = k_2 \frac{\lambda}{\text{NA}^2} \quad (2)$$

where k_2 is process-dependent. Increasing NA improves resolution but reduces DOF, making focus control critical. As shown in Figure 2(b), Song found that raising NA from 0.85 to 1.35 in ArF immersion lithography reduced DOF from ± 200 nm to ± 50 nm, while enabling 38 nm features [2]. Maintaining both resolution and DOF requires co-optimization of optics and resist chemistry, supported by focus metrology and computational lithography [2,6,9].

2.3. Key performance features

Building upon the photochemical mechanisms of photoresists and the optical resolution limits in advanced lithography, this section discusses the performance metrics that directly impact manufacturing feasibility [1,2,6]. While photochemistry governs the fundamental resist response, and optical imaging defines the theoretical resolution ceiling, practical semiconductor production also demands consideration of resolution enhancement, throughput-dose optimization, and precise overlay control. These aspects bridge the gap between theoretical capability and high-volume manufacturing, leading naturally to the trade-off and integration analyses in the following parts.

2.3.1. Resolution enhancement strategies

Resolution can be extended beyond optical limits using multiple patterning approaches, such as spacer-defined intrinsic multiple patterning (SDI-MP) [15]. Material innovations also play a role: optimized CARs enhance sensitivity while mitigating stochastic effects, and inorganic resists provide superior etch resistance and dimensional stability [6,8,9]. Combining optical techniques with advanced materials enables finer patterning without major platform changes.

2.3.2. Fundamental trade-off between throughput and exposure dose

Resist sensitivity determines the required exposure dose, influencing throughput. Higher sensitivity allows faster exposure but may increase stochastic variability [6]. In ArF immersion lithography, adjusting resist thickness and NA can balance resolution, depth of focus, and dose [2]. In EUV lithography, metal-oxide-based resists maintain pattern fidelity at lower doses, improving throughput without sacrificing resolution [7,9].

2.3.3. Overlay accuracy and line-edge roughness control

Overlay accuracy ensures precise alignment between layers, a critical factor in advanced nodes. Moiré fringe-based alignment techniques can achieve sub-nanometer precision [12]. Line-edge roughness, influenced by photon shot noise and acid diffusion, limits pattern fidelity [10]. Inorganic resists inherently suppress LER, while optimized CAR formulations reduce acid diffusion length [6,8,9]. Integrating advanced alignment methods with resist material engineering is essential for meeting stringent overlay and pattern fidelity requirements.

3. Performance analysis and comprehensive comparison of lithography technology

3.1. Comparative performance of major lithography methods

Building on the imaging and resist fundamentals, compares DUV, EUV, and NIL under manufacturing-relevant metrics—resolution, DOF, LER, overlay, and throughput. This establishes a baseline for judging where each platform best fits by layer and application.

3.1.1. Deep ultraviolet lithography

DUV uses 248 nm KrF or 193 nm ArF projection optics; immersion DUV is an enhanced 193 nm implementation that inserts a high-index fluid to raise NA. Both follow Rayleigh scaling Equation (1) and the DOF trend Equation (2): higher NA shrinks CD but compresses DOF. In practice, dry DUV offers maturity and cost efficiency, while immersion extends DUV to smaller pitches before EUV is needed [1-3].

With air in image space ($n \approx 1$), $NA < 1$ caps single-exposure resolution but preserves a wider DOF and process latitude. Advanced nodes, therefore, rely on RET/multiple-patterning, trading simplicity for extra steps and overlay burden. Dry DUV remains attractive for many layers thanks to tool maturity, stable overlay, high uptime, and simpler contamination control, but scaling increasingly favors immersion or EUV for the most critical layers [1]. Replacing the air gap with ultra-pure water ($n \approx 1.44$ at 193 nm) lifts NA to ~ 1.35 , pushing CDs into the ~ 38 nm regime while DOF tightens from $\sim \pm 200$ nm to $\sim \pm 50$ nm as NA rises from 0.85 to 1.35; optimized exposure energy also tends to increase at the smallest pitches [2,3].

3.1.2. Extreme ultraviolet lithography

EUV is a projection method using 13.5 nm light with fully reflective multilayer mirrors and reflective masks in a vacuum [4].

On performance, Levinson's research quantifies the NA/λ trade-off: at $NA = 0.55$, $\lambda = 13.5$ nm, and $k_1 = 0.3$, resolution is about 7.4 nm with Rayleigh $DOF \approx \pm 22$ nm; pushing to $NA = 0.77$ tightens resolution to about 5.3 nm but compresses DOF to $\approx \pm 11$ nm [12]. Throughput is constrained by

laser-produced plasma (LPP) sources (tin-droplet interaction and collector lifetime), so usable source power/stability directly binds productivity [11].

At sub-10 nm half-pitch, photon shot noise and secondary-electron blur raise dose unless resist architectures localize energy/reaction volumes; inorganic/metal-oxide resists improve EUV absorption and the sensitivity-LER balance [5,9].

In conclusion, compared with DUV/immersion, EUV offers higher single-exposure resolution but faces source-limited throughput, narrower DOF, and greater stochastic sensitivity. Progress hinges on LPP source power/efficiency, high-NA optics control, and next-generation inorganic resists [4,5,9,11].

3.1.3. Nanoimprint lithography

NIL patterns by 1×mechanical replication, so intrinsic resolution is defined by the template and resist fidelity rather than k_1 , wavelength, or NA, enabling sub-lithographic features without multiple exposures [1,4]. Without optical focusing, DOF constraints translate into residual-layer and planarization control, with latitude dominated by filling/demolding physics and template uniformity [1]. Nominal throughput is high (single shot per field), yet effective WPH is often limited by defectivity, template durability/cleanliness, and large-area uniformity—key differentiators versus DUV/EUV in HVM [4]. Overlay is addressed by moiré-based alignment; cross-platform surveys and NIL-specific advances (dual-frequency capture and robust fringe-phase extraction) provide precision with practical capture range for in-situ wafer–template alignment [12–14]. Overall, NIL is compelling on resolution and flow simplicity, but competitiveness hinges on sustained control of defects and alignment [1,4].

3.2. Performance trade-offs under key parameters

Having benchmarked the platforms, this part will analyze the parameter-driven trade-offs that ultimately govern HVM feasibility. We structure the discussion around three levers: resolution-throughput (NA, wavelength), exposure dose-LER (resist physics), and overlay-process latitude (metrology and environment).

3.2.1. Resolution-throughput trade-off

By the Rayleigh relation Equation (1), driving resolution by raising NA and shortening λ inevitably compresses DOF and the process window. In 193-nm ArF immersion, single-exposure imaging therefore saturates; further NA increases shrink DOF, so DUV must resort to multiple patterning, adding process passes and lowering WPH [2]. EUV at 13.5 nm shifts the balance: shorter λ improves intrinsic resolution, yet scanner productivity scales with (source power)/(resist dose).

Because stochastic limits push dose upward, WPH falls unless source power rises—an effect intensified on high-NA (0.55) systems with half-field anamorphic scanning and tighter tolerances [4,5]. As a result, EUV throughput hinges on LPP source efficiency/stability and realistic power roadmaps, together with resist sensitivity improvements [4,11]. Nanoimprint can pattern high resolution in a single shot, but defectivity and overlay control currently limit logic-grade HVM, so effective throughput is often set by yield rather than imprint speed [4]. In conclusion, DUV buys resolution with extra exposures, EUV buys it with photons and power, and NIL must buy it with defect control—each path trades resolution for throughput in a different currency.

3.2.2. Exposure dose-ler trade-off

At EUV wavelengths, LER is fundamentally driven by photon shot noise, absorbed dose, and resist blur; simulations show LER falls with increasing dose, at the cost of throughput and energy budget [10]. In positive organic CAR systems, PAG/quencher balance and acid-diffusion control (via polymer architecture, molecular glasses, and additives) shape the sensitivity-LER envelope; suppressing diffusion can preserve low LER without large dose penalties, provided PEB and dissolution kinetics are tightly controlled [6].

In contrast, inorganic or metal-oxide resists (Hf, Zr, Sn, Zn) enhance EUV absorption and form dense cross-linked networks, thereby achieving comparable or improved LER at reduced exposure doses. Continued advances in ligand design and vapor-phase infiltration or dry processing routes further improve sensitivity while simultaneously constraining stochastic variability [7-9]. Taken together, CAR platforms typically achieve lower LER through increased exposure dose or tighter bake process control, whereas metal-oxide and inorganic systems reallocate this balance toward materials engineering, reducing the photon budget required to maintain target pattern fidelity [6-10].

3.2.3. Overlay accuracy and process latitude

As feature sizes shrink, overlay budgets tighten because depth of focus contracts with higher NA, narrowing process latitude and amplifying sensitivity to thermal and vibration disturbances [2,4]. Consequently, even in ArF immersion, retaining margin demands rigorous focus–exposure control and stable environmental conditions [2]. In EUV, reflective optics, vacuum operation, and at high NA (0.55), half-field anamorphic scanning further couples overlay to stage dynamics and thermal management, making feed-forward/feedback metrology loops indispensable [4].

For NIL, moiré-based alignment offers both capture and precision: dual-frequency moiré extends capture range while maintaining nanometer-scale error [13], and improved fringe-phase extraction increases robustness to noise and imperfect fringes, enabling faster in-situ alignment [14]. A broader survey synthesizes error sources (grating quality, gap variation) and mitigation strategies, confirming cross-platform applicability where latitude is most constrained [12]. In short, overlay control is a systems problem: DOF-limited optics and thermos-mechanics set the window, while advanced moiré metrology helps keep multilayer alignment within budget.

3.3. Integration challenges and future trends

3.3.1. High-volume manufacturing integration issues

In HVM, EUV/DUV integration hinges on mask governance (defect avoidance, pellicle reliability, actinic inspection), stochastic-defect control, and tight environmental stability. High-NA EUV adds half-field anamorphic scanning and stricter thermal/mechanical tolerances, coupling overlay and CDU directly to stage dynamics and heat management [4]. Stochastic variability pushes dose upward and stresses source power and energy budgets, with practical limits quantified for advanced nodes [5]. ArF immersion remains robust but inherits DOF-driven latitude loss at high NA and requires rigorous focus/exposure control and metrology [2,3].

Alignment is a cross-platform bottleneck: moiré-based methods offer high sensitivity and error-source mitigation frameworks [12], while NIL-specific advances extend capture range (dual-frequency moiré) and improve phase extraction robustness for in-situ alignment [13,14]. For NIL, large-area uniformity, template durability/cleanliness, and defect repair remain key constraints for

logic-grade HVM despite attractive single-shot resolution [4]. In conclusion, integration success depends on coordinated control of masks, dose, environment, and fast feedback metrology.

3.3.2. Hybrid solutions and sustainable economics

Hybrid flows balance resolution, WPH, and cost of ownership. DUV + multiple patterning extends scaling beyond single-exposure limits but adds steps, cost, and overlay risk [15], anchored by ArF immersion's NA/DOF trade-offs [2]. EUV's shorter λ reduces patterning steps, while computational lithography and source-mask co-optimization widen process windows and suppress defects within realistic power/dose constraints [4,5]. Materials engineering lowers the photon budget: metal-oxide/inorganic resists raise EUV absorption and etch resistance, enabling lower doses at comparable LER; positive-tone CAR advances further tune diffusion and development to protect edges [6-10]. Throughput economics remain governed by (source power)/ (required dose), tying ROI to LPP efficiency, stability, and power roadmaps [4,5,11]. NIL can complement optical flows for replication-oriented layers if alignment and defectivity are controlled via improved metrology and process design [4,13,14].

4. Conclusion

This work compared DUV, EUV, and NIL from fundamental principles to manufacturability metrics and analyzed the parameters that govern high-volume manufacturing. Resolution scaling is inseparable from throughput, as higher NA and shorter wavelengths compress depth of focus and process latitude, necessitating either multiple patterning in DUV or higher exposure doses in EUV. Line-edge roughness emerges as a stochastic constraint, mitigated through resist design strategies such as metal-oxide pathways and diffusion control, while overlay demands co-optimization of optics, mechanics, and metrology supported by advanced moiré-based alignment.

On the tool side, EUV offers superior single-exposure resolution but depends on stable sources, high-NA optics, and mask integrity, whereas DUV remains effective where multiple patterning and mature overlay provide cost advantages. On the materials side, inorganic and hybrid resists reduce the photon budget required for target fidelity, while NIL provides attractive resolution and replication speed but remains constrained by defectivity, template durability, and alignment. Sustainable manufacturing, incorporating solvent reduction, resist reuse, and energy-efficient subsystems, must be regarded as a core design objective across all platforms.

Future progress should emphasize integrated roadmaps linking dose, source power, throughput, and cost, alongside stochastic-aware resist design and computational lithography with source-mask co-optimization. Robust in-situ metrology, moiré-based alignment, and NIL-specific defect prevention are also essential. Ultimately, continued scaling will depend on coordinated advances in optics, materials, computation, and control, pursued not in isolation but as an integrated manufacturing system.

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