A Review of Extreme Ultraviolet Lithography and Its Future Development Trends

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Abstract. Extreme ultraviolet lithography, leveraging a radiation wavelength of 13.5 nm, has become a critical enabling technology for semiconductor fabrication at the 7 nm node and beyond. This paper provides a systematic review of the architectural evolution and development trajectory of EUV lithography, covering its progression from early experimental research in the 1990s to its industrial deployment by leading foundries. The study emphasizes two key performance bottlenecks—EUV light sources and optical systems that are decisive in determining throughput, pattern fidelity, and scalability. In terms of technical advances, this review summarizes recent research efforts to improve laser-to-plasma conversion efficiency, suppress debris contamination, enhance spectral purity, and integrate real-time source control. It also explores innovations in EUV mask design, high-numerical-aperture optical systems, and emerging flat optics technologies. EUV systems face several significant challenges despite continuous progress, including limited source power, thermally induced optical aberrations, and stochastic resist effects at sub-nanometer scales. This paper also discusses several potential solutions, such as free-electron lasers, machine learning-based aberration correction systems, and hybrid lithography strategies that integrate EUV with other patterning techniques. Furthermore, global collaborative initiatives and advancing domestic ecosystems strongly support sustained innovation in this field. By reviewing current progress and outlining future directions, this work aims to offer a comprehensive reference and inspire further exploration in EUV lithography research and industrial implementation.

Keywords: EUV, EUV light source, EUV Optical System, High-NA.

1. Introduction

Semiconductor chips are the fundamental components of modern electronic systems, with widespread applications in smartphones, laptops, data centers, autonomous vehicles, and artificial intelligence hardware [1][2]. As the demand for higher performance, lower power consumption, and greater integration continues to escalate, advanced chip manufacturing technologies have become increasingly critical. Among these, photolithography plays a central role in defining circuit dimensions and device density, and its technological evolution directly influences the progression of the entire semiconductor industry [2].

Driven by Moore's Law, the ongoing pursuit of device miniaturization and performance enhancement has compelled continuous innovation in lithographic techniques. Although deep ultraviolet (DUV) lithography, with a wavelength of 193 nm, has long dominated mainstream fabrication processes, it faces fundamental limitations in achieving sub-10 nm critical dimensions [3][4]. To overcome these resolution barriers, extreme ultraviolet (EUV) lithography has emerged as a key enabling technology, utilizing a significantly shorter wavelength of 13.5 nm [5]. At present, leading foundries such as TSMC, Samsung, and Intel have deployed EUV lithography in high-volume manufacturing at the 7nm node and beyond.

EUV lithography consists of four main technical modules: EUV sources, EUV optics, EUV masks, and EUV photoresists. Each component is unique and essential for achieving sub-7 nm patterning with high resolution and accuracy. The EUV source produces 13.5 nm radiation, typically through laser-produced plasma (LPP) using tin droplets [5][6]. As the primary illumination source, its performance directly influences throughput, stability, and power efficiency. The EUV optics system, central to an EUV lithography (EUVL) tool's performance [7], determines the resolution, pattern accuracy, and alignment precision of the entire process. This module employs multilayer Bragg reflectors instead of conventional lenses to direct and focus 13.5 nm radiation from the mask to the wafer. Because EUV light is strongly absorbed by most materials, these mirrors must operate in ultra-high vacuum environments and maintain minimal wavefront error and thermal deformation [8]. The EUV mask reflects incident EUV radiation to create the aerial image. Due to high absorption of EUV light in typical materials, EUV masks use reflective multilayer structures and require defect-free surfaces [9]. Optional pellicles often protect the mask from particle contamination during scanning. EUV photoresist is a light-sensitive layer coated on the wafer that captures and defines the final pattern [10]. Compared to DUV resists, EUV photoresists face stricter constraints regarding resolution, line-edge roughness (LER), sensitivity, and etch resistance.

Although all four subsystems play critical roles in the overall performance of EUV lithography, this paper focuses specifically on EUV sources and EUV optics, as they represent the most significant performance bottlenecks from a system engineering and electronic design perspective. Accordingly, this paper presents a system-level review of EUV lithography, emphasizing these two modules' structural characteristics, engineering challenges, and future development directions in semiconductor manufacturing and electronic engineering applications.

2. Evolution of EUV Lithography

The relentless scaling-down of semiconductor devices has pushed traditional 248 nm KrF and 193 nm ArF DUV lithography towards their fundamental resolution limits. To sustain Moore's Law, researchers began exploring lithography solutions utilizing shorter wavelengths in the late 1980s, culminating in the proposal of EUV lithography at 13.5 nm [11][12].

Early experimental research on EUV lithography commenced in the early 1990s. In 1991, Hiroo Kinoshita and colleagues in Japan pioneered imaging patterns at 13.5 nm using multilayer mirrors and a synchrotron radiation source. This work laid the theoretical and technical foundation for developing subsequent EUV reflective optical systems [12]. Concurrently, US national laboratories initiated collaborative research programs, including Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories, and Lawrence Berkeley National Laboratory (LBNL). This effort led to the formation of the EUV LLC industry consortium in the late 1990s, which played a pivotal role in unifying the technological roadmap for EUV optics and sources [11][12].

A significant milestone in the evolution of EUV lithography was the transition from laboratory-scale experimentation to industrial application. This shift was catalyzed by coordinated international efforts in the late 1990s, notably by forming the EUV LLC consortium, which unified research across leading institutions such as LLNL, Sandia, and LBNL. A critical breakthrough came in 2010 when ASML delivered its first EUV prototype system, the NXE:3100, followed by the commercial-grade NXE:3300 platform in 2013. These advancements began EUV’s integration into high-volume manufacturing, culminating in its successful deployment at the 7 nm node by TSMC and Samsung in 2018. This transition underscores the culmination of decades of interdisciplinary innovation and system-level engineering, transforming EUV lithography from a theoretical concept into a production-ready technology.

Currently, EUV lithography is extensively employed in fabricating advanced 5 nm and 3 nm logic and memory chips. Next-generation high-numerical-aperture (High-NA) EUV systems are developing actively, featuring an increased numerical aperture (NA) of 0.55. These systems are anticipated to enable the patterning required for sub-2 nm technology nodes.

The development of EUV lithography over the past three decades represents a protracted journey from conceptualization to industrial implementation, necessitating sustained technological accumulation and significant engineering breakthroughs. The EUV light source and optical system have consistently constituted the core technical challenges and primary performance bottlenecks throughout this process. The subsequent sections of this paper will delve into these critical aspects in detail.

3. Advances in EUV Light Source

3.1 Power Scaling under High-NA Constraints

As EUV lithography evolves toward high-numerical-aperture (High-NA) systems—particularly with NA values reaching 0.55—the requirement for increased EUV source power has become one of the most pressing challenges. Present-day commercial systems typically operate at power levels around 250 W. However, to sustain the throughput and resolution necessary for sub-2 nm technology nodes, future systems must achieve power outputs exceeding 500 W. This power escalation must be accomplished without compromising beam quality, system stability, or optical component lifespan.

Recent research has centered on enhancing laser-to-plasma conversion efficiency (CE), a critical factor determining how effectively input laser energy can be transformed into usable EUV radiation. Among the promising approaches is using multi-beam laser configurations that deliver energy from multiple angles or spatial positions, thereby improving the uniformity and energy coupling efficiency. Pulse-shaping technologies, especially dual-pulse irradiation techniques, are also gaining traction. This method uses a pre-pulse to deform or flatten the tin droplet, optimizing the surface for more efficient interaction with the main pulse. This technique has demonstrated improved EUV photon yield and emission uniformity.

Building on this, Atsushi Sunahara et al. proposed an optimization strategy based on 2D radiation hydrodynamic simulations, showing that careful tuning of CO_2 laser parameters—such as increasing spot size, shortening pulse duration, and extending the pre-formed plasma scale length—can push the CE beyond 10%, nearly doubling the performance of current systems by improving absorption, emission profile, and spectral purity [13]. However, increasing power levels inevitably intensify the thermal load on optical elements.

3.2 Advanced Debris Mitigation and Collector Protection

Debris contamination of the collector mirror remains one of the most severe lifetime-limiting factors in LPP-based EUV sources. Research has increasingly shifted toward hybrid mitigation systems combining magnetic deflection fields with inert gas curtains to suppress high-velocity tin particles. This dual mechanism reduces charged and neutral debris before it reaches sensitive optics. At the materials level, self-cleaning collector coatings—such as oxide-based surface layers that catalyze the removal of carbon or tin residues under EUV irradiation—have emerged as a promising approach. While these methods reduce contamination rates, they also introduce trade-offs in EUV reflectivity and long-term stability under active evaluation.

Complementing experimental techniques, recent simulation studies have focused on modeling the physical processes of tin particle deposition. One such study employed the PIC-MCC method to simulate the spatiotemporal behavior of particles generated by pulsed fiber laser interaction with tin droplets in EUV environments. By tracking particle trajectories and quantifying their distribution on the collector surface, the research revealed critical insights into the mechanisms of tin contamination. It provided theoretical guidance for predictive mitigation design [14].

Researchers are now conducting long-term performance tests and materials durability assessments to balance debris suppression and optical throughput, aiming to define engineering standards that extend mirror lifespan without compromising EUV performance.

3.3 Spectral Purity and Out-of-Band Suppression

EUV lithography requires a highly monochromatic light source centered at 13.5 nm, with minimal out-of-band (OOB) radiation, as excess spectral components can cause resist heating, reduce contrast, and increase line-edge roughness. Achieving such spectral purity remains an active area of research.

Recent advancements have been made in optimizing multilayer Bragg reflector coatings, which act as narrow-band filters by selectively reflecting the target EUV wavelength while suppressing unwanted spectral components. Simultaneously, EUV spectral filters with improved rejection characteristics are being developed to eliminate low-energy and high-energy OOB emissions.

At the plasma generation level, researchers explore how varying tin droplet geometry, ambient gas type, and laser pulse parameters can influence the emission spectrum. For instance, fine-tuning pulse energy or using alternative pre-pulse strategies can help narrow the spectral bandwidth at the source itself, reducing the burden on downstream filtering systems.

3.4 Real-Time Source Control and Lithography System Integration

As node scaling advances, lithography tools must maintain increasingly stringent requirements on dose control, spatial uniformity, and overlay accuracy. EUV source systems are tightly integrated with scanner-level control architectures to meet these demands.

One significant trend is the development of real-time beam monitoring systems capable of measuring power stability, spatial uniformity, and beam pointing in situ. These diagnostic tools are coupled with adaptive control algorithms that can rapidly adjust laser pulse timing, energy, or scanner exposure settings based on feedback data.

Furthermore, researchers are exploring the integration of machine learning (ML) models that can predict performance drift or anomalies before they occur. Such predictive control schemes offer the potential to minimize downtime, improve process yield, and enable faster response to system perturbations.

3.5 Exploratory Concepts beyond LPP

In addition to entirely new source architectures such as FEL and Z-pinch, ongoing research explores novel laser-plasma interactions to enhance EUV output within existing frameworks. One such direction involves shifting from traditional nanosecond CO_2 lasers to near-infrared (NIR) femtosecond laser pulses.

A recent study by Jang Hyeob Sohn *et al.* characterized the charge state distributions in tin plasmas driven by 1040 nm femtosecond laser irradiation. Using time-resolved EUV spectroscopy and collisional-radiative simulations, the study revealed that these plasmas predominantly generate Sn^{8+}–Sn^{13+} ions, which are responsible for efficient EUV emission around 13.5 nm. The results indicate that NIR-driven ultrafast plasmas can support highly ionized states suitable for compact and tunable EUV sources [15].

Although the work did not evaluate full system conversion efficiency, it contributes valuable insight into the fundamental plasma conditions that govern EUV photon yield. It offers a foundation for non-traditional drive schemes with potential benefits in debris reduction and source miniaturization.

4. EUV Optical System

4.1 Reflective Mask Design and Metrology

EUV lithography masks differ fundamentally from those used in conventional optical lithography. Since EUV radiation cannot pass through materials, EUV masks must operate in a reflective configuration. A typical EUV mask consists of a multilayer mirror stack, a buffer layer, an absorber pattern, and a protective capping layer.

Research on EUV masks primarily focuses on improving reflectivity, reducing mask-induced imaging aberrations, and minimizing defects. One of the critical challenges is the so-called “mask 3D effect,” where the finite absorber height causes light scattering and phase errors that degrade the aerial image. Advanced absorber materials and optimized pattern geometries are being explored to mitigate this.

Recent progress in EUV mask optimization has also addressed pattern distortion arising from mask thickness, known as the thick mask effect, which can degrade imaging fidelity on the wafer. Pinxuan He *et al.* proposed a linearized EUV mask optimization method based on the adjoint technique to reduce wafer-level pattern distortion caused by thick-mask effects [16]. Their method introduces an efficient gradient computation framework. It incorporates a two-phase optimization scheme: an initial coarse optimization based on linearized gradients and fine optimization using the full gradient after binarization. Experimental results showed a reduction of nearly 50% in iteration count and around 40% in total optimization time, making the method both efficient and scalable. Despite its speed and 3D-mask compatibility advantages, the technique currently struggles with partially coherent illumination and could benefit from further enhancements to improve its manufacturability constraints.

Regarding mask defect inspection, Ansuinelli *et al*. proposed a prior-primed deep neural network (DNN) framework for lensless EUV mask imaging using ptychography [17]. The model reconstructs high-fidelity phase and amplitude images from less than 5% of diffraction data by embedding prior knowledge of mask geometry and material properties into a U-Net architecture. Although not all defects are ideally recovered, the DNN outputs serve as effective initial guesses for iterative ptychographic reconstructions, reducing the number of iterations by up to 70% and accelerating convergence by 8 to 9 times. This approach enables fast, scalable, full-field mask inspection and shows strong potential in die-to-database analysis. Nonetheless, limitations remain in generalization and localization accuracy, which future work may address through domain adaptation and architectural refinement.

4.2 High-NA Objective Lens Design and Emerging Alternatives

The design of high-numerical-aperture (High-NA) objective lenses is central to the success of next-generation EUV lithography and nanoscale optical systems. Traditional High-NA EUV objectives adopt a six-mirror reflective architecture with aspheric surfaces, optimized to operate at 13.5 nm wavelength. These mirrors are typically coated with multilayer Bragg stacks and arranged in a ring-field configuration. Achieving sub-nanometer figure accuracy, nanometer-level alignment, and real-time aberration correction is essential due to the extreme sensitivity to wavefront errors.

Beyond traditional optics, emerging approaches using novel nanomaterials have demonstrated promising results. Chen et al. developed an ultra-thin flat lens (400 nm thick) directly fabricated on a single-mode fiber facet using femtosecond laser direct writing (FLDW) [18]. Based on Rayleigh-Sommerfeld diffraction theory, this lens uses concentric reduced graphene oxide (rGO) rings to modulate both amplitude and phase. The device achieves a numerical aperture of 0.89 and focuses light into a near-diffraction-limited spot (FWHM ≈ 0.68λ), surpassing conventional fiber or metasurface lenses.

The fabrication exploits the significant refractive index contrast between GO and rGO (Δn ≈ 0.8) and avoids using masks or complex lithography. The resulting lens, only 12 μm in diameter, offers low insertion loss and excellent experimental agreement with theory. Despite potential scalability limitations and sensitivity to fabrication conditions, this method presents significant advantages in compactness, efficiency, and integration potential, particularly for applications such as optical tweezers, endoscopy, and on-chip photonics.

5. Challenges

Despite notable breakthroughs in recent years, EUV lithography still faces three core challenges as it advances toward high-volume manufacturing at more advanced technology nodes.

Current LPP sources struggle to deliver power levels exceeding 500 W stably—an essential threshold for high-throughput manufacturing. Low laser-to-plasma conversion efficiency, coupled with severe thermal load and debris-induced contamination under high-power operation, continues to limit source reliability and sustainability.

The introduction of High-NA systems to improve resolution significantly increases design complexity. These systems demand sub-nanometer mirror figure accuracy, nanometer-scale alignment, and real-time compensation for thermal deformation and wavefront aberrations under intense EUV illumination to maintain imaging stability.

Due to the inherently low EUV photon flux and the trade-offs among resist sensitivity, resolution, and etch resistance, key stochastic issues persist—such as line-edge roughness (LER), critical dimension uniformity (CDU) variation, and defectivity. These limitations directly compromise pattern fidelity and yield control.

6. Future Perspectives

To address these persistent challenges, several promising strategies are being explored. For the power limitations of LPP sources, advanced architectures such as free-electron lasers (FELs) and solid-state laser-driven plasma systems are being developed to significantly enhance output power and conversion efficiency. To manage the complexity of High-NA optics, adaptive optics systems and AI-assisted real-time aberration correction algorithms are being integrated to ensure imaging stability under dynamic thermal loads. Meanwhile, to mitigate stochastic patterning effects caused by low photon flux and resist limitations, next-generation resist materials—such as dry-deposited metal-oxide resists (MORs)—combined with optimized exposure conditions and stochastic-aware modeling techniques are being investigated. Collectively, these approaches aim to break current performance bottlenecks and enable EUV lithography to scale reliably toward sub-2 nm nodes.

Global collaboration platforms—such as the U.S. EUV Accelerator program and Belgium's imec laboratories—are accelerating the democratization of EUV technology. Meanwhile, China is making significant strides toward self-sufficiency, with localized integration of LDP light sources and domestically developed lithography tools anticipated to achieve a closed-loop EUV ecosystem by 2025.

Looking further ahead, novel plasma confinement mechanisms, such as magnetically constrained spatial plasmas, may achieve conversion efficiencies exceeding 50%, potentially redefining the EUV paradigm beyond 2030.

7. Conclusion

EUV lithography is expected to directly enable the mass production of sub-2 nm logic devices and ultra-dense 3D NAND architectures, with deployment across leading foundries beginning as early as 2025. Its capabilities will also extend to frontier applications such as waveguide sculpting in silicon photonics, nanometer-precision optics for space telescopes, and diagnostics in nuclear fusion systems—all of which depend on EUV-level resolution and fabrication fidelity.

In summary, this work reviews the current state-of-the-art advancements in EUV lithography, highlighting both their strengths and existing limitations. It further presents future perspectives and potential solutions for overcoming key challenges. The insights provided herein are intended to offer new directions and inspire continued innovation within the EUV lithography community.

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