Dean&Francis
ISSN 2959-6157

Development and Outlook of Extreme Ultraviolet (EUV) Lithography Technology

Zhizhong Chen[1, *]

[1]Engineering, the University of Sydney, Sydney, Australia, 2016
*Corresponding author: zche0476@uni.sydney.edu.au

Abstract:
Extreme ultraviolet (EUV) lithography has emerged as a core approach for expanding semiconductor fabrication beyond the boundaries of deep ultraviolet (DUV) patterning. Due to the ever-diminishing reduction of device size, even utilizing multiple patterning techniques does not address the basic physical issue of optical resolution of conventional 193 nm lithography. This study introduces the concepts of photolithography, the technological revolution from DUV to EUV, and the architectural characteristics of current EUV exposure systems. It addresses additional issues, which include but are not limited to limited source power, mask defects, resist stochastics, multilayer mirror contamination, and pellicle transmission loss. The current research was supplemented with industry roadmaps, and it is concluded in the paper that the future scalability of EUV lithography will be dependent on the use of high-numerical-aperture (High-NA) exposure devices, novel photoresist materials (including metal-oxide resists), and improvements to computational lithography to minimize stochasticity and improve the accuracy of the pattern. This study emphasizes the ongoing relevance of optical lithography for the scalability of semiconductor devices and sheds light on the technical directions needed in order to realise semiconductor units at sub-2 nm.

Keywords: EUV lithography; High-NA systems; photoresist materials; computational lithography; semiconductor manufacturing

1. Introduction

Lithography is one of the core technologies supporting modern semiconductor manufacturing. As transistor dimensions continue to shrink in accordance with Moore’s Law, the limitations of conventional optical lithography have become increasingly prominent. For more than two decades, deep ultraviolet (DUV) lithography using a 193 nm wavelength light source has sustained the production of commercial logic chips and memory chips. However, to achieve process scaling for the 7 nm node and beyond, this technology relies heavily on complex multi-patterning steps. These additional steps not only increase process costs and time consumption but also enhance defect sensitivity.

Extreme ultraviolet (EUV) lithography, operating at a wavelength of 13.5 nm, was specifically developed to address the aforementioned limitations. Its inherently shorter wavelength can directly improve pattern resolution without relying on extensive multi-patterning processes. Nevertheless, EUV lithography faces its own technical challenges, many of which are significantly more difficult than those encountered in DUV lithography.

This paper reviews the fundamental principles of optical lithography, summarizes the evolution toward EUV lithography, elaborates on the technical structure of EUV lithography equipment, and discusses its key challenges and future development directions. The discussion mainly focuses on lithography-related content, with particular emphasis on the complete process flow, photoresist chemical properties, resolution enhancement technologies, and EUV module analysis.

2. Fundamentals of Lithography

Modern lithography consists of a series of tightly controlled process steps that transfer patterns from a mask to the surface of a wafer coated with photoresist. The main steps include wafer cleaning, dehydration baking, adhesion promotion, spin coating, soft baking, mask alignment, exposure, post-exposure bake (PEB), development, and hard baking. Each step plays a crucial role in determining the fidelity of the final pattern and process stability.

Wafer cleaning typically adopts the RCA standard process, using solutions such as a sulfuric acid-hydrogen peroxide mixture and hydrofluoric acid to remove particulate impurities and native oxide layers. The spin coating process determines the thickness of the photoresist (usually between 3000–30000 Å), with the specific thickness depending on the photoresist viscosity and spin speed. Soft baking is used to remove residual solvents, while overbaking may trigger unwanted cross-linking reactions. Mask alignment requires a precision of ±1 μm to ensure correct overlay with previous layers. The exposure process achieves pattern projection through configurations such as contact, proximity, projection, or immersion lithography. Post-exposure bake facilitates acid diffusion in chemically amplified resists, reducing standing wave effects. Finally, depending on whether a positive or negative photoresist is used, the development process removes either the exposed or unexposed regions of the photoresist.

The resolution limit of conventional optical lithography is determined by the Rayleigh criterion:

$$\mathrm{CD}=k_1\frac{\lambda}{\mathrm{NA}}\#(1)$$

where CD is the critical dimension, λ is the exposure wavelength, NA is the numerical aperture, and k_1 is a process-related factor.

3. Transition from DUV to EUV Lithography

193 nm DUV lithography has reached its limits in terms of resolution and process complexity. To fabricate feature sizes below 20 nm, multi-patterning technologies (such as litho-etch-litho-etch (LELE) double patterning or self-aligned quadruple patterning (SAQP)) are required. However, these technologies introduce overlay errors, increase costs by 30%–40%, and yield diminishing returns at advanced process nodes.

EUV lithography uses a 13.5 nm wavelength light source generated by tin plasma, providing a more direct path for process scaling. The shorter wavelength reduces diffraction limits and significantly decreases the number of exposure steps required for pattern fabrication. Currently, the most advanced EUV lithography systems have a numerical aperture of approximately 0.3 [1] and can process about 250 wafers per hour at a light source power of around 400 W.

Unlike DUV lithography equipment, EUV lithography tools cannot use refractive lenses—most materials completely absorb EUV radiation. Therefore, their entire optical system employs alternating silicon-molybdenum multilayer mirrors with a reflectivity of approximately 70%. Meanwhile, the equipment must operate in a vacuum environment to prevent EUV light from being absorbed by

ISSN 2959-6157

air.

4. Optical System and Materials of EUV Lithography

4.1 Light Source

The EUV light source is based on laser-produced plasma (LPP) technology: high-energy lasers strike tin microdroplets, generating plasma with a temperature of up to 200,000°C, which then emits EUV light at a wavelength of 13.5 nm. The system incorporates debris mitigation components to protect the multilayer mirrors from contamination by tin particles.

4.2 Bragg Reflective Optical System

Since EUV light cannot penetrate lenses, the projection system relies on Bragg reflectors—composed of approximately 60 alternating layers of silicon and molybdenum. These mirrors must maintain high reflectivity while minimizing contamination from hydrocarbons and tin debris; even small amounts of carbon deposition can significantly reduce the mirror lifetime.

4.3 Masks and Photoresists

EUV masks are also reflective, consisting of a multilayer stack and a patterned absorber layer. Their defect density requirement is less than 0.01 defects/m², far stricter than that for DUV masks. The pellicle technology for EUV masks remains a major challenge: the pellicle must be extremely thin, highly transparent at a wavelength of 13.5 nm, and thermally stable. However, current pellicles still suffer from significant transmission loss.

In terms of photoresists, chemically amplified resists (CAR) remain the mainstream choice but face the „lithography trilemma“—a trade-off between resolution, line-edge roughness (LER), and sensitivity. Insufficient sensitivity increases exposure dose requirements and reduces productivity, while excessively high sensitivity leads to an increase in stochastic defects. The trade-off between resolution and sensitivity is a key factor limiting the performance of chemically amplified resists [2].

5. Technical Challenges in EUV Lithography

Despite its numerous advantages, EUV lithography still faces several engineering challenges that currently restrict the improvement of its performance and yield:

5.1 Light Source Power and Throughput

The throughput of an EUV lithography scanner is closely related to the light source power. Increasing power poses numerous challenges: higher laser energy leads to increased tin debris, plasma instability, and aggravated mirror contamination.

5.2 Mask Defects and Pellicle Limitations

EUV masks require near-perfect defect control. Due to their reflective optical principle, even defects smaller than 10 nm may be imaged on the wafer. Pellicle technology introduces another layer of complexity: current pellicles have significant transmission loss and are prone to overheating during operation, limiting the process window.

5.3 Photoresist Stochastic Issues

Even though light sources and optics have gotten better, photoresist’s random problems—like photon shot noise and uneven chemical distribution—are still a big obstacle. They make it hard to get good production yields and high-quality tiny features, especially for chips with sub-10 nm technology nodes [3].

At EUV wavelengths, photon shot noise and secondary electron blur cause stochastic fluctuations, leading to defects such as line-edge roughness, microbridges, and pattern breaks. The „three-parameter trade-off“ between resolution, LER, and sensitivity is one of the most fundamental barriers to EUV lithography process scaling [4].

5.4 Vacuum and Contamination Control

EUV equipment must operate in an ultra-clean vacuum environment. Hydrocarbon molecules easily form carbon films on mirror surfaces, reducing reflectivity. Carbon contamination control and debris filtering are critical to ensuring system stability [5].

6. Outlook: High-NA EUV and Computational Lithography

The next generation of EUV systems will be based on high numerical aperture (High-NA) technology, with the numerical aperture increased from 0.33 to 0.55. This improvement enables smaller pattern pitches and reduces reliance on multi-patterning. Meanwhile, high-NA will change the system geometry, and due to the increased incident angle, new mask formats will be required. Recent industry and academic overviews point out that high-NA EUV lithography (NA $\approx$ 0.55) is the next key step to make chips even smaller. It can make image details sharper and cut down on the need for multi-patterning technology, but it also requires stricter control over how thin the resist is and how the manufacturing process is run [6].

In addition to hardware upgrades, computational lithography will play a crucial role. Technologies such as optical proximity correction (OPC), phase-shift masks (PSM), and double patterning have already become indispensable in DUV lithography. However, these technologies still have limitations at nodes below 7 nm [7].

For EUV lithography, inverse lithography technology (ILT), machine learning-based photoresist modelling, and improved optical simulations will be necessary to address stochastic issues and improve dose efficiency.

7. Conclusion

Extreme ultraviolet (EUV) lithography, a type of high-performance next-generation semiconductor manufacturing, is the cornerstone and enabling solution to tackle the resolution and process limitations of deep ultraviolet (DUV) technologies. Using the 13.5 nm exposure wavelength and reflective multilayer optics, EUV lithography generates feature sizes not achievable under conventional 193 nm immersion lithography with advanced multi-patterning schemes. Yet as shown in the work, EUV lithography is still not a mature technology; rather, it remains a complex, highly interdependent system where incremental improvements in optics, materials, and process control for scaling toward sub-3 nm nodes will be needed. The analysis presented in the paper indicates that lithography has not yet taken shape as a mature technology.

These limitations, such as limited source power, mirror contamination, pellicle transmission loss, mask defectivity, and the stochastic behavior of photoresists, have hampered both the throughput and the yield in photoresist manufacturing on a regular basis. Stochastic defects and intrinsic resolution, sensitivity, and line-edge roughness trade-offs stand out among these challenges and are insurmountable by hardware improvements. As it was emphasized in the recent literature, effective progress will necessarily involve a concerted evolution across several domains: the adoption of high-NA exposure systems, the realization of innovative resist chemistries, e.g., metal-oxide resists, and most significantly, the application of cutting-edge computational lithography methods that can realistically reproduce and accommodate imaging modalities unique to EUVs [8]. Recent modelling work with advanced simulation tools like PROLITH shows that, even when optics are optimized, the combined effects of electron scattering and photoresist's random behavior still greatly affect defect rates and chip yields. This makes it clear that computational lithography and resist improvements are just as necessary as high-NA tools [9].

In conclusion, EUV lithography continues to be the basis of semiconductor scaling for the next ten years. But its ongoing progress will rely on advances in optical design, materials engineering, plasma-based light sources, contamination control, and model-driven process optimization. It is only through such integrated progress on EUV lithography that it will reach full potential and assist the journey to nodes of future technology that are below the 2 nm scale.

References

[1] Zhang, G. W., & Zhang, X. T. (2013). Design of High Numerical Aperture Extreme Ultraviolet Lithography Objective Lens. Science Technology and Engineering, 13, 9619–9621.

[2] Xing, Y. M., Hu, T., Fang, W. H., Yu, G. L., Liu, W. X., Xu, Y., Jin, H. A., & Wang, G. J. (2024). Nano-Metal Oxide Cluster EUV Photoresists and Factors Influencing Their Performance.

Science China: Chemistry, 54(12).

[3] K. Cho, et al. (2025) Recent Status of the Stochastic Issues of Photoresist Materials in EUV Lithography. Journal of Photopolymer Science and Technology 35(1):35-40.

[4] Wang, X., He, J. J., Wei, J. L., & Zhu, X. X. (2024). Stochastic Issues in Extreme Ultraviolet Lithography and Their Research Progress. Chinese Journal of Lasers, 51(7).

[5] Huang, K., Zeng, T. T., Shao, J. D., & Zhu, M. Y. (2025). Research Progress on Surface Contamination and Cleaning Technology of Extreme Ultraviolet Multilayer Films. Laser & Optoelectronics Progress, 62(1).

[6] imec. (2021) High-NA EUV lithography: the next major step forward. imec Magazine.

[7] Lin, B. J. (2015). Making lithography work for the 7-nm node and beyond in EUV and 193i. Microelectronic Engineering, 133, 16–27.

[8] Levinson, H. J. (2025). Challenges and limits to patterning using extreme ultraviolet lithography. Journal of Micro/Nanopatterning, Materials, and Metrology, 24(1), 011005.

[9] C. Snyder et al. (2025) EUV resist modeling (PROLITH) for defect printability and stochastic behavior, Proc. SPIE 13425.