Dean&Francis
ISSN 2959-6157

Current Status and Trends in EUV and NIL Lithography Process Development

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Abstract:

Lithography technology is a core process in semiconductor manufacturing. As device dimensions continue to shrink, the limitations of traditional deep ultraviolet lithography in terms of resolution and cost have become increasingly apparent. EUV and NIL have been proposed as next-generation solutions to overcome current process bottlenecks. This paper examines both technologies, covering fundamental principles, process performance, application scenarios, and key challenges. Comparative analysis reveals that EUV, leveraging its short wavelength advantage, demonstrates high resolution and precision in advanced logic processes, making it suitable for nodes at 7nm and below. However, it faces complex equipment, high costs, mask contamination, and photoresist stability issues. NIL, relying on contact-based mold replication, offers high resolution and low cost, enabling sub-5nm feature transfer. It excels in fields like LEDs, photovoltaics, and optical devices, though it remains constrained by issues such as template lifetime, alignment accuracy, and defect control. These technologies are not mutually exclusive but may complement each other in future process chains: EUV handles critical logic layers while NIL serves cost-sensitive and functional structure layers. Research indicates that synergistic development of EUV and NIL can balance resolution and cost, supporting technological evolution in the semiconductor industry. Lithography processes will advance toward higher precision, efficiency, and flexibility. The collaborative application of EUV and NIL is expected to drive industrial innovation and sustainable development.

Keywords: EUV; NIL; Process performance, Synergistic development

1. Introduction

Lithography stands as one of the core processes in modern semiconductor manufacturing. It transfers circuit patterns onto wafers using masks, providing the foundational patterns for subsequent etching and

ISSN 2959-6157

deposition processes. Over the past few decades, as device dimensions have continuously shrunk, lithography technology has also advanced steadily. Deep Ultraviolet (DUV) lithography was previously the mainstream solution. It utilizes a 193-nanometer light source and enhances resolution through water immersion technology and multiple patterning methods. However, this approach encountered obstacles when advancing to nodes below 7 nanometers, requiring progressively more exposure steps, increasing process complexity, and driving up manufacturing costs.

To address these challenges, researchers proposed two new approaches: Extreme Ultraviolet (EUV) lithography and Nanoimprint Lithography (NIL). These represent distinct directions—high-end logic processes and low-cost, high-precision pattern replication, respectively. EUV leverages short-wavelength extreme ultraviolet light to achieve higher resolution, making it suitable for advanced process nodes. NIL employs mechanical imprinting to directly replicate patterns from a master mold, making it suitable for cost-sensitive applications. While EUV and NIL differ significantly in principle and equipment structure, both possess the capability to overcome the limitations of traditional lithography.

This paper examines the fundamental principles, process performance, application scenarios, and key challenges of EUV and NIL lithography technologies. It reviews current achievements to outline their development trajectories. The research aims to conduct a comparative analysis, summarizing differences in resolution, cost, and mass production capabilities, clarifying their respective applicability, and exploring potential synergies in future semiconductor manufacturing. This study provides a reference for subsequent research and industrial practice.

2. EUV Lithography Technology

2.1 Fundamental Principles of EUV Lithography

EUV lithography is an exposure technology utilizing extreme ultraviolet light with a wavelength of 13.5 nanometers. This shorter wavelength enables higher pattern resolution than conventional deep ultraviolet light. The light source for EUV lithography originates from laser plasma, typically generated by bombarding tin particles with a carbon dioxide laser to produce plasma that subsequently emits EUV light.

The system must operate in a vacuum because this light is absorbed in the air. Since EUV light cannot penetrate glass lenses, it does not use lenses. Instead, it employs multiple layers of mirrors to guide the light to the mask. The pattern on the mask is then transferred to the photoresist-coated surface of the wafer via an optical projection system. The entire imaging process relies on reflected light transmission, demanding extremely high precision in the optical components. Each mirror must possess exceptional flatness, with tolerances limited to a few atomic layers. These mirrors are fabricated from specialized materials, employing multilayer coatings to control the wavelength and direction of reflected light precisely [1].

2.2 Process Performance Metrics and Technical Challenges

From a performance perspective, EUV systems have met mass production standards. Current EUV scanners achieve resolutions supporting 7-nanometer logic nodes and smaller, with pattern size uniformity across the entire wafer controlled within 0.5 nanometers. Pattern overlap errors between machines can similarly be controlled around 1.1 nm. Exposure light source power has increased to 250 watts, enabling wafer throughput exceeding 140 per hour. Higher light source power also extends mirror lifespan, reducing system maintenance frequency. These technical parameters demonstrate that EUV technology can now meet advanced logic chip production requirements. Equipment manufacturers are also developing next-generation systems with a numerical aperture (NA) of 0.55, further to enhance pattern resolution and throughput [2]. Despite EUV lithography's formidable capabilities, it still faces several critical challenges. The first issue is mask contamination. EUV systems utilize reflective masks, where even microscopic particles on the mask surface cause pattern defects. Currently, no ideal pellicle material prevents contamination without compromising light transmission. The second challenge is photoresist stability. EUV light's high energy generates substantial secondary electrons. These electrons cause photoresist molecular chain breaks, resulting in rough pattern edges that degrade precision. The third challenge is excessive cost. A single EUV system exceeds $100 million, with vacuum systems, light sources, and mask inspection equipment equally expensive. This forces EUV application to the most advanced process nodes [3].

2.3 Development Trends and Application Directions

ASML and Carl Zeiss have consistently driven the development of high-NA EUV lithography systems in advancing pattern resolution. The latest 0.55 NA high-numerical-aperture exposure tool offers superior pattern resolution compared to traditional 0.33 NA systems. It is expected to achieve single-pass imaging of features below 20 nm minimum pitch, significantly reducing overlay errors and process complexity associated with multiple exposures. This technology enhances contact pattern formation efficiency and substantially increases tool throughput. This technology has been validated on the NXE:3400B platform, offering a viable solution to sustain the feature scaling trend as stated by Moore's Law [4].

To address EUV mask contamination issues, ASML has introduced a polysilicon-based detachable pellicle membrane structure. This design prevents particle adhesion to the mask surface without significantly compromising light transmission. This pellicle exhibits high thermal stability and mechanical strength, enabling prolonged operation under high-power exposure conditions. It is critical to ensure the stable operation of high-throughput EUV production lines. The removable structure also facilitates inspection of mask patterns under DUV or electron beam conditions, enhancing process monitoring flexibility [5].

In materials science, Li et al. pointed out that existing EUV chemically amplified photoresists exhibit excessive acid diffusion and pattern collapse under high-energy short-wavelength exposure, limiting their suitability for low-k processes. They designed a photoresist featuring a branched molecular structure with high absorption efficiency, incorporating heavy elements like iodine to enhance EUV absorption. Simultaneously, hydrogen bonding was introduced to control acid diffusion, improving edge sharpness and pattern fidelity. This photoresist achieves lower line edge roughness and satisfactory size uniformity at 13.5 nm wavelength, meeting high-resolution exposure requirements. Subsequent studies continued employing EUV photoelectron spectroscopy (PES) to track chemical reaction mechanisms, elucidating the removal mechanism of PAG-ions under EUV irradiation and providing theoretical support for material stability assessment [6].

Beyond improvements to light sources and photoresists, EUV systems also face pattern distortion issues stemming from the three-dimensional structure of masks. Particularly when high-angle primary rays strike at specific angles, shadow effects from the absorption layer cause varying degrees of critical dimension deviation in the X and Y directions, leading to reduced pattern fidelity. This phenomenon, the mask 3D effect, is especially pronounced in 13.5nm wavelength EUV systems. Researchers propose implementing a pre-compensation strategy during the mask design phase. By optimizing pattern offset values, potential CD errors in future projections can be corrected in advance. Given that the absorption layer's thickness far exceeds the EUV wavelength, its optical constants—specifically the refractive index (n) and k-value—and its geometric thickness, have been redesigned. This approach reduces interference effects, enabling imaging performance that meets the requirements of low-k processes [7].

Mask and optical systems undergo simultaneous optimization with the ASML NXE:3400B system entering production. Actual data indicate that this platform achieves full-wafer CD uniformity better than 0.5nm in the 5nm logic process, with overlay control achieving better than 1.1nm. This is closely linked to mask 3D effect correction and improved system calibration. Research indicates that combining machine learning with pattern recognition algorithms can precisely model spatial pattern errors caused by 3D masks. This enables further optimization of compensation rules and mask bias strategies, paving the way for new approaches to 3D effect compensation in future high-NA systems [1].

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Although EUV has entered mass production, it continues to undergo upgrades. In the coming years, the industry is pushing for EUV systems with higher numerical apertures—commonly called high-NA EUV. Current equipment operates at an NA value of approximately 0.33, while the next generation aims to increase this to 0.55. A higher NA value translates to greater pattern resolution, enabling the realization of smaller feature sizes. However, high-NA systems introduce new challenges: the depth of field for patterns gradually decreases, demanding even greater precision in focusing accuracy; distortion in mask patterns also intensifies. Equipment manufacturers must comprehensively upgrade projection optics, mask design rules, and exposure control software. Photoresist materials must also adapt to energy density shifts caused by high NA. Researchers are developing highly sensitive, low-absorption chemical amplification photoresists. These materials must maintain stable resolution under EUV's high-energy exposure while preventing edge roughening and pattern collapse.

ISSN 2959-6157

3. NIL Lithography Technology

3.1 Process Principles and Classification

Nanoimprint lithography transfers patterns by imprinting through a mold. It does not rely on optical imaging but instead presses a template with micro-nano structures directly onto a photoresist layer, "imprinting" the pattern onto the surface of a wafer or other material. This process resembles stamping with a seal called "contact lithography."

Based on different curing methods, NIL can be categorized into several types. Thermal imprinting deforms polymers under high temperature and pressure conditions; Ultraviolet Nanoimprint Lithography (UV-NIL) operates at ambient temperature and pressure, utilizing ultraviolet light to trigger polymerization reactions that cure liquid photoresist. Jet and Flash Imprint Lithography (J-FIL) is considered a variant of UV-NIL. It employs inkjet technology to precisely deposit photoresist onto the wafer surface, followed by imprinting and curing. Among these methods, J-FIL is most suitable for large-area semiconductor manufacturing. It offers advantages such as lower pressure and temperature requirements, minimal material damage, and transparent templates for pattern transfer.

3.2 Technical Advantages and Application Scenarios

The most significant advantage of NIL is its high resolution. Since it is not constrained by light diffraction, it can theoretically achieve sub-5-nanometer patterns. Current experiments have already achieved 2-nanometer resolution. Additionally, NIL equipment features a simple structure requiring no complex optical systems. The entire process eliminates exposure and development steps, reducing manufacturing complexity. This translates to significantly lower equipment costs than traditional lithography systems like EUV. NIL also enables direct replication of three-dimensional patterns—such as microlenses, nanocolumn arrays, or bilayer structures—an efficient capability for flexible electronics, microfluidic chips, and structured optical components.

Given its high precision and low cost, NIL shows promising applications across multiple fields. During LED chip manufacturing, NIL can imprint microstructures onto sapphire substrates to enhance light extraction efficiency and brightness. NIL creates micro-nano surface textures for photovoltaic cells that improve sunlight absorption, thereby boosting conversion efficiency. This process has achieved stable implementation on large-sized silicon wafers. NIL can imprint micro-patterns onto plastics and other flexible substrates in flexible electronics and wearable devices. Since it avoids high-temperature processes and does not damage the substrate, NIL is also employed to produce AR waveguides, microlens arrays, and patterned metal lenses, driving optical components toward thinner, lighter, and higher-precision designs [9].

3.3 Technical Challenges and Development Directions

Although NIL offers numerous advantages, it faces significant challenges in practical production operations. A primary issue is template contamination. Given that NIL employs a contact process, templates are susceptible to contamination from residual adhesive and particles, compromising the quality of subsequent patterns. Another challenge is pattern alignment, particularly during multilayer pattern stacking. NIL's alignment precision is insufficient to meet the overlay requirements of advanced nodes. Even with the introduction of precision alignment mechanisms in some systems, the overall performance still falls short of EUV. Mold lifespan also poses a limiting factor, particularly in high-volume manufacturing. Templates are highly susceptible to wear or damage during repeated imprinting cycles. This necessitates the development of more wear-resistant template materials while simultaneously enhancing the stability of template replication techniques. Process consistency is also impacted since NIL employs a point-to-point pattern transfer approach. Achieving high yield and low defect rates requires meticulous control across multiple stages, including template fabrication, imprinting parameters, and photoresist formulations.

Sreenivasan's team pioneered the J-FIL process to address template contamination and defect control. This method eliminates the high-temperature, high-pressure requirements of conventional thermal imprinting. Instead, it precisely deposits low-viscosity UV-curable photoresist onto the wafer surface via inkjet printing. A transparent mold then cures the resist under UV light exposure. This approach significantly reduces residual layer thickness while minimizing particle contamination accumulation during imprinting. J-FIL enables sub-20 nm pattern transfer on large-size wafers with low defect density. Its key innovation lies in the "droplet distribution + UV curing" combination, ensuring uniform material contact and preventing thermal stress-induced uneven resin distribution and residue buildup inherent in conventional thermal imprinting [10].

Molecular Imprints collaborated with SEMATECH and others to implement systematic improvements to address the challenge of insufficient alignment accuracy during NIL multilayer stacking. They introduced high-contrast alignment markers and validated these on standardized large-size templates. Experimental data demonstrates that the Imprio500 system achieves 10 nm-level overlay accuracy on 300 mm wafers, approaching the ITRS specifications for advanced nodes. Compared to traditional optical lithography, NIL alignment still faces disadvantages. However, these studies confirm that NIL's stacking accuracy has significantly improved through optimized marker design, enhanced machine vision system performance, and the adoption of interferometric alignment detection. Its defining characteristic is the transition of alignment strategies from purely mechanical to a parallel optimization approach combining "optical assistance + software algorithms," advancing the application potential of NIL in logic and memory chip manufacturing [11][12].

Regarding mold longevity and material durability, researchers increasingly recognize that mold wear and contamination pose critical barriers to scaling NIL from lab to mass production. Recent review studies indicate that employing ultra-wear-resistant materials with atomic-level smoothness and low surface energy—such as quartz composites and multilayer anti-adhesion coatings—can substantially extend mold lifespan and reduce defects during repeated imprinting cycles. Advancements in mold replication techniques, such as rapid transfer processes using master and slave molds, have substantially reduced individual template costs and risks, making large-scale production economically viable. Alongside explorations in roll-to-roll continuous manufacturing and parallel multi-template imprinting, researchers have introduced real-time optical inspection and machine learning algorithms to monitor and predict alignment errors and defect distributions. This intelligent process control feature enables adaptive correction during high-speed imprinting, maintaining high yield and low defect levels in large-scale manufacturing. It lays a solid foundation for the industrialization of NIL [9][13].

4. EUV vs. NIL Comparative Analysis and Synergy Trends

4.1 Principle Differences

EUV and NIL exhibit distinct operational principles. EUV employs optical imaging through remote exposure techniques, utilizing 13.5-nanometer extreme ultraviolet light. It relies on multi-layer mirrors to project patterns from masks onto wafers without direct contact with the wafer surface.

NIL is a contact-based pattern replication process. It involves pressing a patterned template onto a photoresist surface, then using ultraviolet light or thermal energy to cure the resist layer, thereby transferring the pattern. NIL does not utilize optical systems or projection imaging modes. Given EUV's non-contact nature, contamination risks and pattern damage are minimal. However, the system is complex and costly. While NIL's structure is relatively simple, templates wear out easily, and the contact process imposes higher material demands.

4.2 Resolution and Pattern Accuracy

NIL holds a natural advantage in resolution. It directly replicates nanostructures from the mold without optical diffraction limitations. Experiments have achieved 2-nanometer line widths and even replicated three-dimensional structures. In contrast, EUV resolution is constrained by wavelength and numerical aperture, currently achievable below 7 nanometers but requiring complex optical systems. Regarding pattern uniformity, EUV employs precision reflective optics and advanced exposure control to maintain sub-nanometer edge roughness and dimensional uniformity. NIL, however, suffers from localized errors during large-area processing due to factors like uneven template contact pressure and unstable photoresist spreading.

4.3 Cost and Mass Production Capability

EUV equipment and its maintenance incur extremely high costs. A complete EUV system costs over $100 million, requiring auxiliary facilities such as vacuum chambers, high-power laser light sources, and mask inspection systems. This makes EUV primarily deployed in the mass production of high-end logic chips. NIL equipment features a simpler structure, with costs representing only a fraction of EUV system investments. It requires no expensive optical components or vacuum systems. NIL demonstrates significant cost advantages, particularly in mid-to-low-end processes, functional layers, and patterned sapphire substrates. However, during mass production, NIL faces challenges such as template wear, irregular colloid diffusion, and particle contamination. These issues necessitate solutions like template replication, automated processing, and defect repair systems [10].

4.4 Process Adaptation Scenarios

EUV lithography primarily targets logic chip manufacturing, especially for nodes at 7 nanometers and below. Traditional lithography can no longer meet resolution requirements within this range, making EUV a viable replacement solution. TSMC, Intel, and Samsung all employ EUV systems in their high-end processes.

NIL is better suited for non-traditional semiconductor applications, such as LED manufacturing, solar cells, micro-optical components, flexible electronics, and microfluidic chips, enabling patterning on diverse material surfaces. EUV and NIL are not competitive but complementary: EUV addresses challenges at the most advanced nodes, while NIL serves cost-effective scenarios and diverse structural requirements.

ISSN 2959-6157

5. Potential Future Convergence Development

For future chip manufacturing, EUV and NIL are expected to achieve a synergistic relationship rather than a replacement relationship. EUV excels at handling logic layers with high pattern density and stringent overlay accuracy requirements. At the same time, NIL is better suited for scenarios demanding higher cost efficiency and topography control with moderate precision needs. Research and industry efforts are exploring combined EUV-NIL workflows. One approach involves using NIL to replicate microstructure patterns for EUV masks or functional layers. NIL's ability to replicate high-precision structures at low cost reduces EUV mask fabrication complexity and shortens production timelines. Another approach involves applying NIL to auxiliary layer structures unattainable via EUV lithography, such as microlens arrays, interference gratings, and waveguides. While high overlay precision is unnecessary for these structures, microstructure accuracy demands remain stringent, making NIL the more suitable technique for their fabrication [14].

The Texas Institute for Electronics (TIE) has acquired Canon's commercial NIL system for industrial-scale research and has attempted to deploy EUV and NIL equipment on a single production line, enabling them to work in tandem. For instance, EUV is used for transferring main circuit patterns, while NIL is employed to fabricate interference layers, scattering structures, or optical tuning structures. This "hybrid lithography" approach reduces costs and expands chip functionality. Additionally, another integration approach warrants greater attention: NIL leverages its low-cost, high-precision replication capabilities to manufacture EUV mask templates, thereby streamlining the EUV front-end preparation process [15].

6 Conclusions

The Texas Institute for Electronics (TIE) has acquired Canon's commercial NIL system for industrial-scale research and has attempted to deploy EUV and NIL equipment on a single production line, enabling them to work in tandem. For instance, EUV is used for transferring main circuit patterns, while NIL is employed to fabricate interference layers, scattering structures, or optical tuning structures. This "hybrid lithography" approach reduces costs and expands chip functionality. Additionally, another integration approach warrants greater attention: NIL leverages its low-cost, high-precision replication capabilities to manufacture EUV mask templates, thereby streamlining the EUV front-end preparation process.

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