

Research on Critical Technologies of Nanoimprint Lithography Process in Semiconductor Manufacturing

Cunhui Liu

*Department of Systems Engineering, City University of Hong Kong, Hong Kong, China
cunhuiliu2-c@my.cityu.edu.hk*

Abstract. Nanoimprint lithography (NIL), as a non-conventional pattern transfer technique, presents unique competitiveness in the fabrication of semiconductor structures for medium-to-low resolution, cost-sensitive, and high-volume applications, owing to its advantages in high resolution, high throughput, low cost, and scalability. Compared with conventional lithography, NIL achieves high-precision pattern transfer beyond the optical diffraction limitation by directly imprinting and transferring patterns through mechanical contact, without relying on complex optical systems, thereby significantly reducing equipment and operational costs. This article systematically reviews the fundamental principles of NIL and its major process types, including thermal nanoimprint lithography (T-NIL), ultraviolet nanoimprint lithography (UV-NIL), and roller nanoimprint lithography (R-NIL), elaborating on the characteristics and applicable scenarios of each in terms of resolution, process conditions, substrate compatibility, throughput, and cost. Furthermore, a multi-dimensional comparison is conducted to analyze NIL's competitive positioning within the current universal lithography technology landscape, while potential future development directions are outlined. Although NIL still faces challenges such as limited mold lifetime and pattern flexibility, advancements in material engineering, process optimization, and technology integration are expected to broaden its industrialization prospects.

Keywords: nanoimprint lithography, semiconductor process, T-NIL, UV-NIL, R-NIL

1. Introduction

The semiconductor industry has undergone exponential growth in recent decades, achieving deep integration with modern societal infrastructure. As a core technology in semiconductor manufacturing, lithography plays a crucial role in determining the performance and advancement of integrated circuits and the semiconductor sector. With the ongoing pursuit of smaller feature sizes, traditional lithography techniques are increasingly confronted with more complex challenges. Deep ultraviolet lithography (DUV) and extreme ultraviolet lithography (EUV) are two of the most employed methods of lithography currently. Both have allowed integrated circuits to reach the 7 nm node and beyond. However, as process complexity increases, so do design and equipment costs. In the meantime, resolution approaches optical system theoretical limitations, worsening the inherent contradictions. Given such factors, there is an urgent need for novel or complementary technologies

that strike a balance between high precision and productivity, especially in cost-sensitive applications, complicated structures, and large-area pattern replication.

In this context, NIL has quickly become a new non-conventional lithography technique that opens up a new way for semiconductor device fabrication. NIL gets around the diffraction limitations of traditional optical lithography by employing mechanical means to imprint nanoscale patterns. As a result, NIL makes patterns with high precision while decreasing costs as well as rendering the system less complicated. NIL has also evolved into various variants, indicating loads of potential for application in numerous scenarios. NIL can be divided into T-NIL, UV-NIL, and R-NIL, among others, based on how the substance is cured and how the entire process is organized. NIL exhibits considerable potential in the domains of semiconductor production and micro/nanofabrication for its high resolution, high throughput, and low cost [1].

With the continuous emergence of novel functional devices, NIL technology plays an important role in multiple cutting-edge fields. In 2024, Yamakawa et al. discussed the application strategies of Canon's NIL system in semiconductor back-end-of-line processes and demonstrated preliminary results of meta-optical elements designed for the visible spectrum [2]. In the same year, Cui et al. proposed a flexible mold NIL approach, successfully realizing microstructure printing on curved substrates, offering a low-cost and high-quality solution for flexible substrate semiconductor device fabrication [3]. In 2025, Cao et al. explored the advantages and current status of NIL applications in patterned sapphire substrates (PSS), LED structures, and photovoltaic cells, highlighting their significant potential in future industrialization efforts [4].

However, NIL still faces several challenges in its industrialization process. Mold fabrication and material selection require further investigation to achieve high-quality pattern transfer. Issues such as mold lifetime and imprint defects also limit the stability and pattern fidelity in large-scale manufacturing. Nevertheless, such challenges fail to overshadow the core competitiveness of NIL in industrial applications characterized by medium-to-low resolution, low cost, and high throughput. With ongoing process improvements and synergistic industrial collaborations, NIL is expected to advance further in semiconductor industrialization and achieve broader commercial adoption.

The article aims to analyze the advantages, limitations, and application scenarios of dominant NIL processes through a comparative study of key technologies, as well as to evaluate their competitive positioning within related lithography techniques. By systematically summarizing the current development status of NIL and its industrial applications, this work provides cross-industry comparable metrics and future development directions, offering valuable references for subsequent research.

2. The basic principle and classification of nanoimprint lithography

NIL represents a cutting-edge nanofabrication technology that duplicates patterns directly through the physical deformation of resist materials. The primary principle is to employ a mold with nanoscale features to replicate these patterns onto a substrate surface through imprinting. Heating, UV curing, or other treatments can help with the process, which makes it possible to fabricate nanostructures with high accuracy within 10 nm [5]. This approach gets rid of the necessity for optical imaging, without the diffraction restriction that regular photolithography faces. Therefore, the method makes the procedure less complicated while also allowing for nanoscale resolution that is unattainable through conventional lithographic processes.

2.1. Thermal NIL (T-NIL)

The initial nanoimprint lithography methods employed thermoplastic polymer resists, which are now classified as T-NIL. In standard planar T-NIL manufacturing, the thermoplastic resist is evenly spin-coated onto the substrate and then heated up to its glass transition temperature. At this temperature, the resist is often, allowing a mold with nanoscale features to be pressed into it under applied pressure. After the resist fills the mold cavities and conforms to its surface, the system is cooled to solidify the pattern. The mold is then removed, transferring the nanostructures onto the substrate [1]. The general process is illustrated in Figure 1.

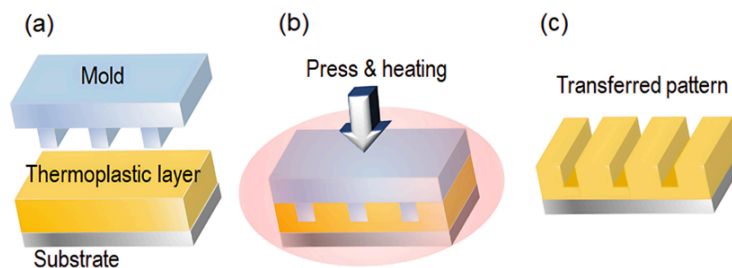


Figure 1. T-NIL process with a planar mold [1]

T-NIL demonstrates exceptional resolution capabilities, achieving feature sizes as small as 5 nm. The heating stage helps get rid of air bubbles that are trapped in the imprint resist. Nevertheless, the frequent heating and cooling cycles make the whole process take longer and reduce the throughput. The high temperature and pressure may also cause pattern distortion and make it hard to remove the mold [6].

2.2. Ultraviolet NIL (UV-NIL)

Ultraviolet NIL is a fabrication technique used to replicate nanoscale patterns through curing polymers that are sensitive to ultraviolet light. The procedure starts with the precise attachment of a photosensitive polymer onto the substrate, which is typically accomplished by spin-coating or drop-casting. Next, a transparent mold is lined up and pressed into the resist layer to fill the cavities. Then, the resist is exposed to ultraviolet light through the mold, starting the polymerization process. Finally, the mold is taken off to reveal the pattern printed on it. UV-NIL works with feature sizes smaller than 10 nm and holds a straightforward procedure that is compatible with multilayer alignment. However, practical implementation confronts obstacles such as bubble flaws and residual layer control. Various coating methods also have an immense impact on the quality of the pattern, and thus should be tuned based on the features of the pattern [7]. The loading effect during imprinting can also easily result in pattern deformation and depth non-uniformity, reducing the accuracy and optical performance of the patterns [8]. All of these factors make it hard to fabricate structures with high precision.

2.3. Roller NIL (R-NIL)

Roller NIL employs a cylindrical mold to apply pressure to complete pattern transfer, which is distinct from conventional plate-to-plate nanoimprint lithography (P2P-NIL). R-NIL maintains the high-resolution advantage of conventional planar imprinting while significantly improving throughput through enabling continuous, high-volume processing. High imprint and demolding

forces may lead to mold deformation and make it hard to demold in large-area planar imprinting. The linear contact mechanism in R-NIL effectively mitigates these issues and facilitates enhanced precision in the regulation of mechanical pressure. R-NIL can be divided into roll-to-plate (R2P) and roll-to-roll (R2R) modalities, as shown in Figure 2. The R2R format is particularly suited to continuous fabrication on flexible substrates. Despite ongoing challenges in achieving precise equipment alignment, controlling polymer curing, and managing demolding, R-NIL is progressing toward industrial-scale implementation due to its high-throughput potential [9].

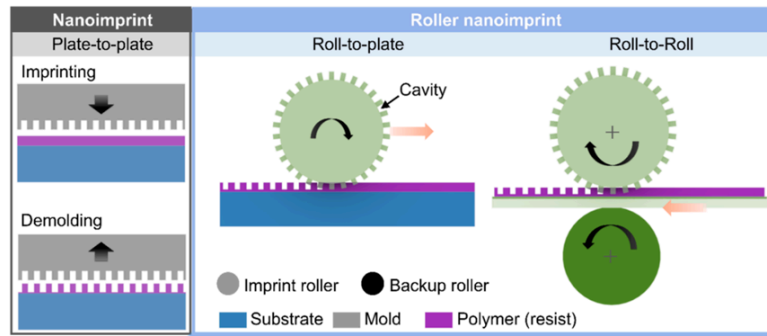


Figure 2. The schematics showing the principle of NIL and R-NIL [9]

3. Analysis of critical technologies of nanoimprint lithography

3.1. Comparative analysis of universal NIL techniques

Table 1 compares the three universal nanoimprint lithography techniques—T-NIL, UV-NIL, and R-NIL—across several key dimensions. To begin with, all three techniques are based on the direct physical imprinting of a mold, while differing in their curing mechanisms. Specifically, T-NIL relies on the thermal deformation and cooling solidification of thermoplastic polymers, representing a physical process. In contrast, UV-NIL employs a chemical process involving the UV-induced curing of photoresists. R-NIL integrates linear physical imprinting with various curing mechanisms, offering higher complexity in system integration.

Table 1. Comparison of universal NIL techniques

Items	T-NIL [1]	UV-NIL [6]	R-NIL [10]
Principle	Physical process	Physical and chemical processes	Physical and chemical processes
Condition	High temperature and high pressure	Room temperature and low pressure	Room temperature and low pressure
Substrate	Rigid substrate	Rigid/flexible substrate	Flexible substrate
Resolution (nm)	5	10	50
Throughput (m ² /h)	4.24	>4.24	300
Cost	High	Medium	Low
Scalability	Hard to expand on a large scale	Suitable for small batch and medium area production	Suitable for industrial-grade continuous mass production

It is worth noting that the imprinting principle directly determines the process conditions, which in turn affect substrate compatibility. The T-NIL principle demands high temperature and pressure,

up to 365 °C and 10 MPa, respectively, suggesting that only rigid substrates can be employed [1]. In contrast, UV-NIL benefits from UV curing, which allows for imprinting at room temperature and under low pressure, giving it more substrate selection flexibility. R-NIL works better for continuous processing on flexible substrates, indicating substantial potential for industrial-scale mass production.

Furthermore, the high-temperature and high-pressure requirements of T-NIL, along with its P2P intermittent imprinting mode, result in long cycle durations and low throughput. Such a situation leads to raised production costs and limited application scenarios. UV-NIL provides advantages for medium-scale fabrication because of its faster curing, lower processing costs, and higher material utilization. R-NIL, which is distinguished by its continuous imprinting, is an ideal technique to manufacture functional devices on a large scale with high-level throughput. Even though the initial cost of R-NIL equipment and master molds appears extremely high, this technique ultimately possesses the lowest cost per unit of production, rendering it highly competitive for large-scale industrial manufacturing.

In summary, each universal NIL technique exhibits distinct advantages and inherent limitations, which dictate their respective application domains. Despite its high processing costs and rigorous operating conditions, T-NIL achieves superior patterning resolution. Given this, it proves extremely advantageous for fundamental research that aims to reach resolution limits and the fabrication of nanoscale devices with high precision. UV-NIL is employed widely in optics, displays, and flexible electronics for its gentle processing conditions and rapid curing capability [3,11]. Due to its continuous operation, high throughput, and low unit cost, R-NIL represents the key direction for the industrialization of NIL, offering strong potential for large-area manufacturing.

3.2. Competitive positioning of NIL in similar lithography techniques

As the resolution of semiconductor devices comes to the sub-10 nm range, advanced lithography processes confront significant technical obstacles and raise cost constraints. Currently, the universal lithography techniques include extreme ultraviolet lithography (EUV), electron beam lithography (EBL), and the rapidly evolving NIL. These technologies exhibit distinct characteristics in terms of resolution, cost, patterning flexibility, and large-area manufacturing capability, leading to different application orientations.

Among these techniques, EUV is considered the primary competitor to NIL. By utilizing high-energy ultraviolet light, EUV achieves state-of-the-art resolution and has become the universal technology for advanced chip manufacturing. Complex patterns below 5 nm can be realized, and even 3 nm resolution is becoming feasible. However, EUV systems are extremely complex, requiring vacuum chambers and high-powered lasers, which result in very high costs. Insufficient throughput further limits the applicability of EUV in high-volume production [12]. Another lithography technique, EBL, represents a maskless patterning approach. EBL offers exceptional resolution and considerable patterning flexibility through programmable control. Nevertheless, compared with optical lithography, its serial writing process is time-consuming and severely affects production efficiency; therefore, merely suitable for mask fabrication and small-scale production [13].

As a technique that directly transfers nanoscale patterns onto substrates through mechanical imprinting, NIL overcomes the low-throughput limitations of EUV and EBL, enabling continuous and high-throughput production of semiconductor devices. Although it's a relatively simple process that results in lower resolution compared to other advanced lithography methods, NIL offers significant advantages in cost reduction and scalability. NIL-based on template molds has

demonstrated fabrication performance comparable to EBL in applications such as metalenses [11]. Due to its cost-effectiveness, NIL is particularly suitable for resolution-relaxed, cost-sensitive applications, including memory devices, displays, micro/nanophotonic components, and biochips. Moreover, various NIL derivatives—such as T-NIL, UV-NIL, and R-NIL—allow for process customization tailored to different material systems and resolution requirements.

However, NIL exhibits certain limitations compared to alternative nanofabrication approaches. Compared to alternative methods, NIL exhibits limited patterning flexibility. Once the mold is fabricated, it cannot be modified, lacking programmability and making it less suitable for small-batch or rapid-iteration production. In addition, the imprinting process is prone to defect generation, which can significantly reduce mold lifetime and pattern fidelity, posing practical challenges to the broader adoption of the technology.

Overall, rather than serving as a direct replacement for universal lithography techniques such as EUV, NIL is better regarded as a novel and complementary strategy toward the development of an ideal future lithography platform. By integrating with other lithographic methods, NIL can effectively bridge gaps in cost and efficiency for specific application scenarios. In highly integrated applications that do not demand ultimate resolution, NIL is expected to become one of the most strategically significant lithography approaches.

4. Conclusion

This article systematically reviews the fundamental principles of NIL and comparatively analyzes the characteristics of universal processes (T-NIL, UV-NIL, and R-NIL) along with their competitive positioning against similar lithography techniques. Each NIL variant exhibits distinct advantages in resolution, substrate compatibility, production cost, and scalability. The synergistic integration of these complementary technologies can substantially enhance the functional capabilities and application scope. Through comparative analysis with dominant lithography methods such as EUV and EBL, this work highlights the unique strengths of NIL in cost-sensitive and medium-to-low precision applications, while also acknowledging its limitations in pattern flexibility and mold durability.

The research and application of NIL not only break through the technical bottlenecks of traditional lithography but also offer a novel pathway for future semiconductor manufacturing at the industrial level. This article provides an effective reference for the industrial development of NIL through a systematic summary of its key processes and a comparative analysis of its competitive positioning, clearly delineating its broad application prospects and future development directions. The development of NIL focuses on several key directions. On the one hand, optimizing mold materials and fabrication processes is crucial for improving pattern fidelity and mold lifetime. Sustainable materials, such as biodegradable nanostructured templates, may also be considered to address ongoing challenges in NIL development. On the other hand, synergistic integration with other technologies warrants attention, including the incorporation of multilayer alignment techniques and the use of AI for dynamic parameter optimization. NIL is currently at a critical stage, transitioning from technological maturity to industrial deployment. Through material and process improvements as well as technological integration, NIL is poised to become one of the most strategically significant core technologies in semiconductor device manufacturing.

References

- [1] Unno, N. and Mäkelä, T. (2023) Thermal nanoimprint lithography—a review of the process, mold fabrication, and material. *Nanomaterials*, 13(14), 2031.
- [2] Yamakawa, Y., Ifuku, T., Yonekawa, M., Sato, K., Saito, T., Ito, T., Yamamoto, K., Hiura, M., Takabayashi, Y. and Sakai, K. (2024) Nanoimprint lithography performance and applications. *Proc. SPIE 13216, Photomask Technology 2024*, 132161I (12 November 2024).
- [3] Cui, S., Sun, K., Liao, Z., Zhou, Q., Jin, L., Jin, C. and Zhou, S. (2024) Flexible nanoimprint lithography enables high-throughput manufacturing of bioinspired microstructures on warped substrates for efficient III-nitride optoelectronic devices. *Science Bulletin*, 69(13), 2080-2088.
- [4] Cao, Y., Ma, D., Li, H., Cui, G., Zhang, J. and Yang, Z. (2025) Review of Industrialization Development of Nanoimprint Lithography Technology. *Chips*, 4(1), 10.
- [5] Yang, Z. (2024) Application and challenges of nanoimprint lithography technology in China's semiconductor industry. *China Science and Technology Industry*, (6), 50–53.
- [6] Li, J. (2023) Nanoimprint lithography process and its manufacturing equipment. *Electronic Equipment for Electronic Industry*, 52(4), 14–19.
- [7] Rimböck, J., Schuster, P., Vsetecka, L. and Thanner, C. (2024) UV Nanoimprint Lithography—Impact of Coating Techniques on Pattern Quality. *Nanomanufacturing*, 4(1), 69-80.
- [8] Alnakhli, Z., Liu, Z., AlQatari, F., Cao, H. and Li, X. (2024) UV-assisted nanoimprint lithography: the impact of the loading effect in silicon on nanoscale patterns of metalens. *Nanoscale Advances*, 6(11), 2954-2967.
- [9] Peng, Z., Zhang, Y., Choi, C. L. R., Zhang, P., Wu, T. and Chan, Y. K. (2023) Continuous roller nanoimprinting: next generation lithography. *Nanoscale*, 15(27), 11403-11421.
- [10] Oh, D. K., Lee, T., Ko, B., Badloe, T., Ok, J. G. and Rho, J. (2021) Nanoimprint lithography for high-throughput fabrication of metasurfaces. *Front. Optoelectron.*, 14(2), 229–251.
- [11] McClung, A., Torfeh, M., Einck, V. J., Watkins, J. J. and Arbabi, A. (2024) Visible metalenses with high focusing efficiency fabricated using nanoimprint lithography. *Advanced Optical Materials*, 12(9), 2301865.
- [12] Rahman, A. (2024) The Lithography Race of NIL vs. EUV: The need for T-ray Nanometrology. 10.13140/RG.2.2.34506.38089.
- [13] Basu, P., Verma, J., Abhinav, V., Ratnesh, R. K., Singla, Y. K. and Kumar, V. (2025) Advancements in Lithography Techniques and Emerging Molecular Strategies for Nanostructure Fabrication. *International Journal of Molecular Sciences*, 26(7), 3027.