

I. Resistless nanofabrication by stencil lithography: A review

Short summary

This review presents stencil lithography as an alternative to traditional resist-based lithography. It extensively discusses stencil lithography's principles, advantages, limitations, and applications in nanoscale device fabrication, especially for situations requiring patterning on delicate, non-conventional substrates or integrating sensitive materials. This technique addresses several core manufacturing challenges in MEMS/NEMS. First, it eliminates photoresist use, enabling fabrication on flexible, fragile, or bio-compatible substrates. Then, it's essential for prototype and mass manufacturing because of rapid, scalable patterning across large areas. More but not less, it can reduce contamination and thermal exposure which are critical for sensitive MEMS/NEMS structures due to resistless and direct deposition.

Take away messages

1. Stencil lithography is now a mature, clean, and flexible nanofabrication approach. Although challenges remain in terms of resolution and stencil lifetime, further optimization of stencil design, adoption of dynamic modes, and integration with other process steps could enable stencil lithography to play a significant role in MEMS/NEMS fabrication and even in industrial-scale manufacturing.
2. Eliminates photoresist residues and chemical/thermal contamination
3. By moving the stencil relative to the substrate, arbitrary patterns can be written in a single process. This is ideal for rapid prototyping and programmable nanomanufacturing.
4. There're wide range of application already demonstrated, such as cell and protein patterning, CMOS integrated sensors, plasmomic biosensing, and so on.

Outlook

Before achieving true atomic-scale contacting, there are some challenges that the author mentioned. The current stencil resolution must be improved by roughly an order of magnitude by reducing both geometrical blurring and surface diffusion. Also, epitaxial growth must be implemented under carefully controlled temperature condition to ensure atomic precision. At the end, they also highlighted that scanning probe microscopy must be operated at cryogenic temperature to suppress diffusion and enable stable atomic manipulation.

Year of review / any new one?

Published: 2015

A 2017 review by Ke Du et al. ("Stencil Lithography for Scalable Micro- and Nanomanufacturing") updates the field, discussing rigid vs. flexible stencils, dynamic techniques, and future programmable nanolithography trends.

Quality of the review

This review paper provides a comprehensive and well-structured overview of stencil lithography, including its principles, fabrication methods, resolution limits, and applications. The authors did not simply summarize text from the literature — they created original

schematics (Fig. 1. (b), Fig. 5. (a)). In addition, they offered their own discussion on the limitations and future perspectives of the technique.

II. Lithography, metrology and nanomanufacturing

Short summary

This article compares top-down and bottom-up nanomanufacturing approaches, as well as the metrology required for cost-effective, high-yield production. Top-down methods, such as optical lithography, achieve very high precision (overlay < 9.5 nm), which is suited for high-value ICs, with a justified use of expensive metrology. Nanoimprint lithography (NIL) surpasses optical limits and is well-suited for creating single-layer, densely packed patterns; however, it presents challenges related to defects and multilayer overlay. Bottom-up techniques, such as block copolymers and DNA origami, offer high throughput and low cost for large-area periodic patterns, but struggle with maintaining long-range order and controlling defects. The authors emphasise matching metrology complexity and cost to product value. This article also emphasises the need for cost-effective, real-time metrology integrated into manufacturing tools. For MEMS/NEMS, a hybrid approach of top-down processing for overlay-critical layers and NIL/DSA for simpler features, balanced by tiered metrology, can optimise cost, speed, and yield.

Take away messages

1. Although the precision requirement for the high end IC and the low cost novel devices are similar. The fabrication and metrology must be optimize to maintain high throughput and cost.
2. Choose patterning routes by defect tolerance, overlay need, and \$/m² target
3. For MEMS/NEMS, maintain deterministic top-down processing for overlay-critical layers, utilise NIL/DSA for single-layer or periodic features mplement tiered, in-line metrology that balances cost, speed, and yield
4. Utilise layered metrology, such as SEM/AMF for calibration and for rapid measurement of periodic structures; employ scatterometry and X-ray diffraction.

Outlook

For future work, the authors emphasize the need for the closed-loop process control to provide high throughput nano manufacturing

Year of review / any new one?

Published: 2011.

There are a few reviews on a similar topic, one of the most recent reviews is *Integrated metrology for advanced manufacturing* by Archenti et.al in 2024.

Quality of the review

This paper comprehensively emphasises the right technique selection to maintain the balance between the throughput of manufacturing and cost of manufacturing. The paper expands the

resolution versus throughput plot to include inkjet and letterpress, showing a second trend line that also incorporates a third axis view (resolution, throughput, defectivity/complexity). It also adds a new plot for throughput versus yearly revenue.

III. **Self-assembly from milli- to nanoscales: methods and applications**

Short summary

One of the main challenges in MEMS and NEMS is the packaging and integration of heterogeneous components—such as sensors, actuators, circuits, and optoelectronic devices—since their fabrication processes are often incompatible. Conventional robotic pick-and-place techniques, while reliable at larger scales, become inefficient and problematic at micro/nanoscale due to fragility, stiction (below $\sim 300\ \mu\text{m}$), accuracy/throughput trade-offs, and the serial nature of the process. Self-assembly (SA) emerges as a promising alternative: it is inherently parallel, scalable across millimeter to nanometer sizes, and reduces the need for direct manipulation. Recent advances in programmable SA enable not only efficient integration comparable to pick-and-place but also the construction of complex 3D micro/nanosystems, making it highly relevant for future MEMS/NEMS manufacturing.

Take away messages

1. Multiple physical principles (capillary, magnetic, electric, biological) enable diverse SA strategies at size regimes from milli- to nanoscales. No single SA method is universally superior: each shines at specific size ranges, environments, or integration tasks. Their complementarity is crucial, e.g., shape matching for coarse alignment at microscale precision + capillarity for fine tuning at nanoscale precision.
2. Parallelism and scalability are the main advantages over serial robotic methods.
3. Recent demonstrations show SA can go beyond integration to create new classes of 3D and hierarchical micro/nanosystems.

Outlook

Authors emphasize the need for improved control over yield and defects, more programmable interactions, and integration with microfabrication standards to make SA industrially viable. They also highlight the potential of hybrid approaches, where SA is combined with top-down lithography and robotic manipulation, to achieve programmable, scalable, and high-performance MEMS/NEMS architectures.

Year of review / any new one?

Publish: 2009

A few more review papers on the topic of self-assembly for MEMS have been published afterwards. 1. A more general review in the domain of self-assembly was summarized in 2014 (DOI: 10.1049/iet-nbt.2014.0020). 2. Microelectronic devices made through 3D self-assembly methods were reviewed in 2020 (DOI: 10.1002/adma.201902994).

Quality of the review

This review goes beyond listing papers by providing an original table which compared the general methodologies for self-assembly. It offers excellent insights in terms of failure analysis, limitations, and process selection criteria during the discussion of each methodology.

IV. Mitigating stochastics in EUV lithography by directed self-assembly

Short summary

The paper focuses on mitigating stochastic defects in extreme ultraviolet (EUV) lithography by leveraging directed self-assembly (DSA) of block copolymers. EUV lithography faces increasing stochastic variability due to photon shot noise and molecular inhomogeneity, especially as critical dimensions shrink. This is highly relevant for MEMS/NEMS, where precise nanoscale patterning is essential for functional reliability and scaling.

In this paper, the impact of DSA is investigated for: using lamellae forming block copolymers, nanoscale line/space (L/S) structures and using a cylinder forming BCP material to form hexagonal contact hole (HEXCH) patterns

The paper first explains the process flow for rectification of L/S and HEXCH patterns. Introduces critical design aspects and determines features that can be quantitatively analyzed to examine the quality of developed patterns. With image processing, the paper compares the results for EUV resist patterns (printed with sub-optimal exposure conditions to increase the defect density) and those of the DSA rectification process. The paper concludes that by integrating DSA with EUV, defectivity and critical dimension uniformity can be improved, enabling more reliable nanoscale devices.

Take away messages

1. Key metrics for L/S patterns: roughness (not investigated in the paper) and defectivity.
2. Key metrics for HEXCH patterns: local critical dimension uniformity (LCDU), ellipticity, and pattern placement error (PPE).
3. For L/S patterns:
 - 1) The main defects are bubble defects that tend to appear more towards the edge of the wafer.
 - 2) Dislocation and line break defect types are rare.
 - 3) There is a high potential for bridge type defects, which is attributed to excess polystyrene residues inside the block copolymer film. To reduce the number of bridge defects of the DSA rectified patterns, the BCP formulation was adjusted.
4. For HEXCH patterns:
 - 1) LCDU is improved from 2.26 nm to 1.52 nm after the DSA rectification process and pattern transfer.
 - 2) The ellipticity of the DSA pattern after wet development increases (worse than EUV resist pattern). After pattern transfer to 13 nm SiN the it reduces. The reason: the ellipticity obtained after wet development only characterizes the top interface of the BCP film, which is not constant throughout the vertical direction of the BCP film.

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- 3) PPE increases by the DSA rectification process, also after pattern transfer to SiN. Therefore, finding strategies to control the PPE of the DSA patterns is a crucial requirement for further process improvement.
5. To optimize DSA performance:
 - 1) Increasing the BCP film thickness from 36 nm to 54 nm: slightly increases LCDU but results in a significant reduction in PPE.
 - 2) Increasing the dry etch time by 30% and 60% is beneficial for all three metrics considered in this study.
 - 3) Addition of a second thermal anneal step at lower temperature with minimal impact on PPE but considerably improving the LCDU of the DSA pattern.

Outlook

Authors suggest that future work should focus on controlling placement error, optimizing materials (e.g., high- χ block copolymers), and refining process integration to further enhance manufacturability.

Year of review / any new one?

Published: 2023

The paper is not a review paper, and it has been reviewed later in the following review paper: *Review of Directed Self-Assembly Material, Processing, and Application in Advanced Lithography and Patterning, 2025, by Cheng et al.*

Quality of the review

The paper provides both a brief review and mainly original contributions. Authors present experimental findings, which includes defect classifications, SEM images, and wafer-scale analyses. From the quality point of view, we believe that the paper delivers what it is supposed to. Nevertheless, there are many aspects that the paper does not delve into, and instead, it suggests to perform a deeper investigation.

V. Thermal scanning probe lithography—a review

Short summary

Microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) enable thermal scanning probe lithography (t-SPL) through cantilevers with integrated heaters that provide ultrafast, localized heating. This technology offers key advantages over conventional lithography: heat as a universal stimulus allows nanoscale modification across diverse materials; the absence of charged particles prevents damage in sensitive systems such as 2D materials; and the technique achieves sub-10 nm resolution with precise 3D (grayscale) patterning capability. Combined with a compact, cost-effective setup, these strengths make MEMS/NEMS-based t-SPL a highly versatile tool for nanomanufacturing, with applications spanning electronics, photonics, and biotechnology.

Take away messages

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1. Nowadays, t-SPL can achieve sub -10 nm lateral and <1 nm vertical resolution with excellent reproducibility
2. t-SPL uses heat instead of charge particales, which avoid radiation damage and making it suitable for sensitive and 2D materials
3. AFM integration can ensure precise depth control and accurate overlay
4. This technique has the compatibility with standard process like etching, lift-off, and other steps.

Outlook

The authors foresee t-SPL evolving into a versatile nanofabrication tool for both research and specialized industrial applications. Current throughput is limited by the speed of a single tip. Parallel operation of hundreds or thousands of tips, as pioneered in IBM's Millipede project, could bring t-SPL closer to industrial-scale production. While t-SPL offers unmatched resolution and versatility, it is slower for large-area or low-resolution structures. Combining t-SPL with faster methods like laser lithography allows hierarchical patterning (fine nanoscale + coarse microscale), making the technology more practical for real device fabrication. The advancement of this technology will also be dependent on the new material development and emerging applications in electronics, photonics, quantum devices, and biotechnology, especially where damage-free, high-resolution patterning is required.

Year of review / any new one?

Published: 2020

In 2022, Albisetti et al published *Thermal Scanning Probe Lithography* on nature review methods primers. It updates t-SPL fundamentals, key parameters, reproducibility issues, and highlights applications from biomedicine to nanoelectronics (e.g., chemical gradients, spin-wave devices, 2D-material FETs), concluding with future research directions.

Quality of the review

The author provides detailed tables that compile and compare data from the literature, including the resolution, speed, limitations, and potential applications of each approach, as well as a comprehensive list of materials that have been patterned with t-SPL. These tables and illustrations are original contributions that synthesize information from many sources into a single, coherent reference.