Summary: Review paper

Giada Romano - LAFT
Yagmur Ceren Alatas - LAFT
Alexandre Domenech - AQUA
Suraj B. Gaikwad - AQUA
Prabhleen Singh - AQUA

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École
polytechnique
fédérale
de Lausanne

Summary: Research papers

- Paper 1: Prabhleen Singh
- Paper 2: Giada Romano
- Paper3: Yagmur Ceren Alatas
- Paper4: Suraj B. Gaikwad
- Paper5: Alexandre Domenech

List of papers: Reviewed

- Lander Verstraete, Rémi Vallat, Julie Van Bel, Min-Gi Jo, Philippe Bézard, Hyo Seon Suh, "Enabling chemically amplified resists towards tight pitch EUV patterning by directed self-assembly," Proc. SPIE 13427, Novel Patterning Technologies 2025, 134270D (25 April 2025); https://doi.org/10.1117/12.3051663
- O. Vazquez-Mena, L. Gross, S. Xie, L.G. Villanueva, and J. Brugger. 2015. Resistless nanofabrication by stencil lithography. Microelectron. Eng. 132, C (January 2015), 236–254. https://doi.org/10.1016/j.mee.2014.08.003
- Liddle, J. Alexander, and Gregg M. Gallatin. "Lithography, metrology and nanomanufacturing." Nanoscale 3.7 (2011): 2679-2688.
- Verstraete, Lander, et al. "Mitigating stochastics in EUV lithography by directed self-assembly." Novel Patterning Technologies 2023. Vol. 12497. SPIE, 2023.
- Mastrangeli M, Abbasi S, Varel C, Van Hoof C, Celis JP, Böhringer KF. Self-assembly from milli- to nanoscales: methods and applications. J Micromech Microeng. 2009 Jul 8;19(8):83001. doi: 10.1088/0960-1317/19/8/083001. PMID: 20209016; PMCID: PMC2832205.

Enabling chemically amplified resists towards tight pitch EUV patterning by directed self-assembly

- **Short description:**
  - This paper demonstrates how combining directed self-assembly (DSA) with chemically amplified resists (CARs) enables finer, more uniform EUV lithography patterns, using advanced block copolymers and optimized processing to achieve improved line/space and contact hole arrays at the nanoscale. The results support higher precision and density, which are valuable for advanced semiconductor, MEMS, and NEMS manufacturing.
- **Relevance for MEMS/NEMS**
  - MEMS/NEMS devices increasingly require smaller, more precise patterns as dimensions and integration scale down.
  - The combined DSA and CAR strategies discussed can help push lithography limits, enabling fabrication of sub-30 nm structures, which is valuable for miniaturized sensors, actuators, and transducers in MEMS/NEMS.
  - Achieving low line edge/width roughness and precise pattern placement is crucial for reliable MEMS/NEMS operation, where structural variations can affect mechanical, electronic, or optical performance.
  - The demonstrated approaches—optimized stacks, high-chi BCPs, and controlled processing—enable higher uniformity and placement accuracy, thus supporting consistency and repeatability in MEMS/NEMS arrays and batch production.

Key takeaway messages

- Combining DSA and CARs enhances EUV lithography: Integrating directed self-assembly with chemically amplified resists enables patterning of extremely tight pitches, improving both resolution and roughness control for semiconductor applications.
- Material stack choice is critical: The use of a SiCN/amorphous carbon underlayer minimizes line wiggling and delivers superior line/space pattern transfer, indicating that underlying stack optimization directly impacts pattern fidelity.
- High-chi BCPs and film thickness boost accuracy: High-chi block copolymer materials and increased BCP film thickness reduce line width roughness and pattern placement errors, supporting improved uniformity and defectivity of contact hole arrays.
- Process window and defect control are advanced: Optimization of annealing conditions for thicker BCP films and adopting high-chi materials broaden the process window and enable better defect management, which is key for manufacturing scalability.

Outlook provided by the authors

- The authors highlight the need for further investigation into the origins of line edge roughness (uLER) during stack transfers and patterning.
- They suggest that continued development of high-chi BCP materials and further process optimization will be essential to fully realize the benefits of DSA in advanced lithography.
- The outlook envisions DSA-enhanced EUV patterning as foundational for future semiconductor nodes, with possible applications extending to finer, denser, and more complex MEMS/NEMS architectures and other nano-devices.

Other relevant papers

- The reviewed paper "Enabling chemically amplified resists towards tight pitch EUV patterning by directed self-assembly" was published in 2025.
- A 2025 review titled "Review of Directed Self-Assembly Material, Processing, and Application in Advanced Lithography and Patterning" (Micromachines, May 2025) provides a comprehensive overview of DSA lithography advances, including materials and processing developments integrating DSA with EUV, DUV, e-beam, and nanoimprint lithography.
  - *Cheng, X.; Liang, D.; Jiang, M.; Sha, Y.; Liu, X.; Liu, J.; Cao, Q.; Shi, J. Review of Directed Self-Assembly Material, Processing, and Application in Advanced Lithography and Patterning. Micromachines 2025, 16, 667. https://doi.org/10.3390/mi16060667*
- Thus, the 2025 paper is current, and very recent and ongoing research continues to report advances in the same field, with updated comprehensive reviews available from this year that expand and complement the findings in the paper you provided.

Quality of review paper

- The 2025 paper "Enabling chemically amplified resists towards tight pitch EUV patterning by directed self-assembly" presents original experimental work rather than a pure literature review. The authors contribute new data on:
  - Optimization of material stacks (SiCN/aC bilayers) for DSA pattern transfer,
  - Characterization of line edge/width roughness (uLER/uLWR) after etch,
  - Impact of high-chi block copolymers on pattern roughness and placement,
  - Effect of BCP film thickness and annealing on defectivity and placement accuracy of contact hole arrays,
  - Quantitative analysis using SEM imaging and machine learning defect classification.
- They include original figures, tables, and quantitative data derived from their own experiments and metrology, such as:
  - SEM images,
  - Roughness characterization graphs,
  - Defect density as a function of process parameters,
  - Comparative results for different underlayer stacks and BCP materials.

Resistless nanofabrication by stencil lithography

- **Short description:**
  - Stencil Litography (SL) consists in vacuum deposition through micro-nano stencils that are very thin membranes with engineered apertures approaching the surface. When using physical vapor deposition, such as thermal evaporation, the flux of the incoming atoms will be partially blocked by the stencil -used as a mask and only where the membrane stencil has apertures atoms can reach the surface underneath and create a pattern on it. Stencil lithography is a convenient way to directly fabricate nano wires and their contact pads. Stencils are fabricated by UV or e-beam lithography and aperture etching in a very thin silicon-nitrite membrane.
  - SL requires the use of physical vapor deposition technique (PVP), which has a long mean free path, such as thermal, or e-beam evaporation which occurs in high vacuum. PVP allows for the creation of small structures with sharp edges. Fig.2 shows the geometry during the stencil lithography with the dimensions and locations of the source, the stencil apertures, and the substrate. Assuming line of sight deposition, straight lines, one can predict very precisely the pattern as a function of the various parameters. In real SL, patterns are always widened compared to an ideal PVP process, as shown in the picture. This is mainly due to the presence of a gap between the surface and the stencil and the use of non-punctiform source

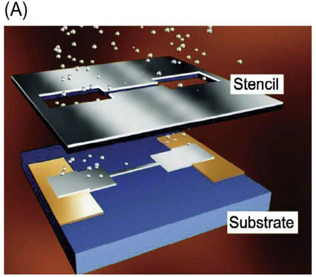


Figure 1

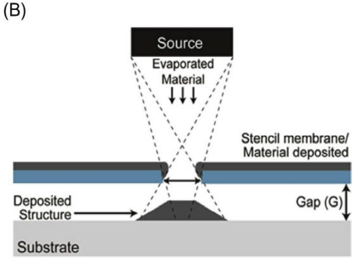


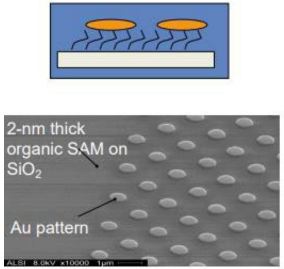
Figure 2

Resistless nanofabrication by stencil lithography

  - Another contribution to the pattern widening is not only geometry, but also the surface diffusion of the arriving thermal atoms. Therefore, highest resolution can be achieved by placing the stencil very close to the substrate, and by placing the emission source as far away as possible.
- Nanopatterning using SL has many advantages:
  - No resist processing: for example, SL allows the creation of metal patterns without the use of photo resist, reducing risk for contamination which may affect the electronic transfer property in the nano structure
  - Easy manipulation and implementation: without using photoresists, some process steps such development and baking can be avoided
  - Reusability: stencils can be reused many times, allowing for cost-effective pattern replication using various materials onto different substrates
  - Dynamic stencil lithography: SL has the capability to move the stencil during deposition, allowing the fabrication of structures with variable thickness and diverse shapes using a single stencil (mask).
- SL is applicable to virtually any surface and substrate material, and it becomes extremely important when trying to pattern on “exotic” surfaces, such as:
  - Self-Assembled Monolayers (SAMs): Fig.3 represents an example of sub micrometer gold dots can be deposited directly on organic, self-assembled monolayers on a SiO2 substrate, which is an important layer for organic electronic devices. These are the gold dots directly on the SAM patterned through the openings of a stencil
  - Freestanding MEMS: Fig.4 shows nano structures directly deposited on freestanding MEMS cantilevers. Particularly, it represents gold nano dots deposited on an AFM cantilever and the AFM tip.
  - CMOS circuits: Fig.5 shows stencil nano structures that are directly and locally deposited onto a CMOS circuit without the need for resist chemistry and temperature steps. This allows for post-processing highly sophisticated CMOS circuitry by locally adding metallic or other material nano structures.

Resistless nanofabrication by stencil lithography

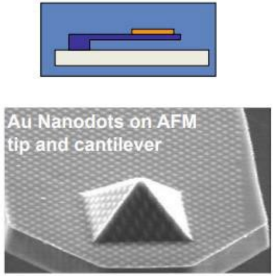
On SAM



E.A. Speets et al., Twente University (2004)

Figure 3

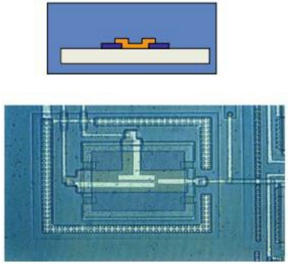
Freestanding MEMS



Brugger et al., Twente University (2000)

Figure 4

Post CMOS



Arcamone et al., CNM Barcelona (2009)

Figure 5

- The main challenges correlated with SL for nanoscale patterning include:
  - Blurring: patterned structures are always larger than the aperture because of the gap between the surface and the stencil itself. Limit in resolution is limited by the divergence in the flux of material and the degree of freedom of the deposited material diffusing on the surface.
  - Aperture clogging: when the deposited thickness of the material is similar or larger than the stencil aperture size, material can accumulate on the stencil and inside the aperture, limiting the patterning resolution and reproducibility.
  - Membrane stability: mechanical robustness, membrane stress issues and alignment overlay are problems related to the stencil. A trade-off in the stencil fabrication is needed to take into account several factors, such as the size of the aperture and the overall membrane size.

Resistless nanofabrication by stencil lithography

- key take away messages from paper; what outlook do authors provide where the field may go next?
  - SL is a resistless technique for micro-nano patterning, theoretically applicable to any surfaces and substrates. Stencils can be reused many times ➔ cost-effective nanofab technique
  - Stencils can be fabricated by UV or EBL depending on the smallest size of the needed aperture (down to 50nm)
  - Main challenges include blurring and clogging of the stencil. Pattern widening is given by geometry and surface diffusion.
  - Main advantages of SL include patterning on SAMs ➔ organic electronics, patterning on freestanding MEMS ➔ where use of resist is restricted, post CMOS circuits ➔ contact pad, to avoid use of chemistry (contamination) and high T steps (baking)

  Outlook include growing use of SL in a wider range of applications from photonics to biosensing, thanks to its simplicity for fast replication and resistless fabrication to achieve high clean structures.
- year of review paper; are there any newer review papers published?
  - Paper published in 2014. A later published review paper on the topic is the following: “Stencil Lithography for Scalable Micro- and Nanomanufacturing.” Micromachines 2017. It is a comprehensive update on resistless, reusable stencil approaches, mask materials (SiNx, Si, polymer), stacking, and large-area scaling. Link: Stencil Lithography for Scalable Micro- and Nanomanufacturing

Resistless nanofabrication by stencil lithography

- Since then, stencil/nanostencil lithography is typically covered (a) as a section inside broader or application- specific reviews, or (b) it is mentioned in specific primary papers.
  - Broader or application-focused reviews/perspectives that include stencil: “Scalable, Lithography-Free Plasmonic Metasurfaces by Nano-Patterned/Sculpted Thin Films for Biosensing”, Frontiers in Sensors (2022). It discusses resist-free approaches for metasurfaces and references nanostencil routes as scalable options.
  - Very recent primary papers with substantial background sections:
  - “Direct nanopatterning of complex 3D surfaces and self-aligned superlattices via molecular-beam holographic lithograph”, Nature Communications (2025). It presents a shadow-mask-based approach and provides a concise overview of NSL fundamentals and limitations.
  - “On-chip stencil lithography for superconducting qubits.”, arXiv (2025). It presents intro/background sections capture present-day stencil mask materials, cleaning/thermal budgets (to 1200 °C), and integration concerns.
- Quality of review paper: did authors make original content e.g. figures/tables to compile data from literature?
  - No specific tables representing a trend in the use of SL have been inserted. Neither figure representing a summary of all the interesting applications deriving by SL. However, many pictures have been reprinted based on the literature mentioned in the text, helping the reader to stay up-to-date during the reading

Lithograpy, metrology and nanomanufacturing

- **Paper summary:**
  - Top-down (lithographic techniques) and bottom-up (self-assembly) are evaluated from throughput, resolution (accuracy), defectivity, and complexity perspectives.
  - Top-down fab. (optical and electron(ion beam lith.): used in IC fabrication.
  - Lithography limitations:
    - Resist: necessary to have a resist that yields accurate features at low exposure doses. The goal is to increase the lithography throughput (use less dose- have accurate features). Trade-off between the resolution and exposure dose is a limitation-optical
    - Electron /ion beam lithography: deviation in the beam trajectory due to interactions between the particles cause blurring in the final structure, loss of accuracy.
  - Maskless lithography: (I) multiple beams: reduce the deviations due to interaction between particles (ii) imaging optical systems (lenses)
  - Ultra high vacuum scanning tunnelling microscope, feedback-controlled lithography, single atom positioning: ultimate resolution but very slow (several nm square in few hours)

Lithograpy, metrology and nanomanufacturing

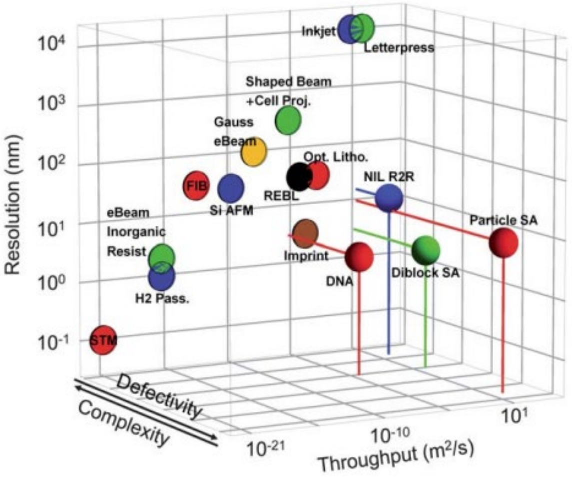
- **Dip-pen nanolithography**: scanning probe-based lith. system, under ambient conditions, applicable for biomolecule patterning.
- **Nano-imprint lithography**: does not suffer from optical/ion/electron beam limitations, but, can produce 1x of the features on the mask, no scale and distortion corrections. On going work: multi-level NIL patterning masks.
- **Bottom-up fabrication**: Nanoparticles, deblock copolymers, DNA self-assemble on a surface because of the underlying surface topology or chemistry. Self-assembly occurs over a small area (particles of interest respond to their local environment).
- **Complexity** refers to the fabrication complexity required to extend these local interactions toa long-range level (bottom-up fab.)
- **Metrology**: affects the overall cost/ throughput significantly. 2 types: (I) in depth, slow metrology to develop the process and assess the critical factors (ii) minimal and high speed metrology-control the process once it is developed.
- Top down and bottom up fab requires different level of metrology precision (more defects are OK in bottom up, also there is no alignment, no long-range coherence necessary)
- Resolution of the patterning tool does not necessarily have to be same as the resolution of metrology tool. Ex. Gratings: optical properties are first analysed w. Spectrometry (lower resolution than fab. tool) and then overlapped with the simulation results.

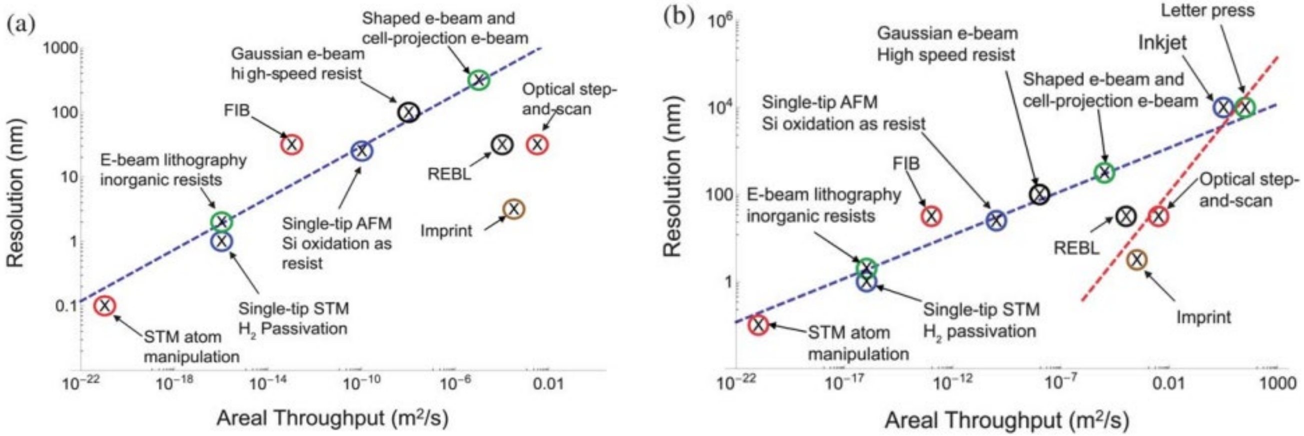
Key messages and latest review papers

- Bottom-up fabrication: prominent technique for patterning on small substrates (short range interactions, not wafer level fabrication). Long range interactions, larger surface patterning is a challenge.
- Metrology: tool and choice of metrology method depends on fabrication method (top-down/bottom-up), required level of precision and accuracy and the overall cost of the process/cost of the final device. Need for cost-efficient metrology tools with high accuracy.
- Top-down fabrication:
  - Main goal is to obtain (multi-level) patterns with high accuracy, resolution at high-throughput.
  - Optical lithography: a key limitation is the absence of a resist that allows accurate patterning at low dose.
  - NIL: promising technique as it doesn’t suffer from conventional lithography limitations but mostly for single level patterning
- Advances, Application and Challenges of Lithography Techniques (2024): Review of nanolithography techniques (conventional optical photolithography, extreme UV lith, NIL). State-of-art in next generation lithography (NGL, all the aforementioned techniques are included) is presented.
- Evolution in Lithography Techniques: Microlithography to Nanolithography (2022): Review on optical lithography, extreme ultraviolet lithography, electron beam lithography, X-ray lithography, and ion beam lithography. The evolution of these techniques, the tools designed to increase their resolution and resists are also discussed. Comparison of mask/maskless lithography techniques.
- Promising Lithography Techniques for Next-Generation Logic Devices (2018): Next generation lithography techniques (NGL): extreme UV lithography, maskless lith, directed self-assembly, NIL are explained, compared. State-of-the-art is outlined.

Quality of review paper

- The authors explain and compare nearly all the patterning techniques available at the time of the paper. There are detailed plots regarding the comparison of these techniques (resolution, throughput, complexity)
- Same plots are extended for both top-down and bottom up techniques
- Effect of metrology precesiness on the overall cost and differences in metrology requirements for top-down and bottom up fab. are also explained in depth.





Mitigating Stochastics in EUV Lithography by Directed Self-Assembly

- **Introduction:**
  - Lithography is the process of "printing" tiny patterns on silicon wafers using light, forming the basis of modern integrated circuits.
  - Extreme Ultraviolet (EUV) lithography, which uses **13.5 nm** wavelength light, enables patterning of extremely small features required for advanced semiconductor nodes. However, EUV suffers from stochastic effects, meaning random variations occur in the printed patterns.
  - These variations are caused by limited photon counts (photon shot noise) and uneven distribution of resist chemistry at the nanoscale. They result in defects such as line breaks, bridges, missing holes, and critical dimension variation.
  - Directed Self-Assembly (DSA) of block copolymers (BCPs) is a complementary approach to EUV, where polymer molecules naturally organise into ordered patterns of stripes or dots. With a guiding pattern defined by EUV, DSA can "rectify" or heal defects, improving pattern fidelity and reducing stochastic variability

Previous work

- Earlier research identified stochastic defects as a major limitation for single-exposure EUV lithography.
- Studies showed that critical dimension uniformity (LCDU) worsens at low exposure doses, and defects such as line-edge roughness and missing contacts become more frequent.
- Traditional solutions, such as increasing exposure dose or optimising resist chemistry, reduce defects but hurt throughput and increase cost.
- Directed self-assembly has been proposed as a solution since the 2000s, with prior work demonstrating that block copolymer self-assembly can repair line roughness, enhance contact hole circularity, and even multiply pattern density. However, challenges remained in defectivity, placement accuracy, and integration with EUV flows.

This work

- In this paper, Verstraete et al. (2023) present a study on mitigating stochastic defects in extreme ultraviolet (EUV) lithography through the use of directed self-assembly (DSA) of block copolymers.
- The work focuses on developing and evaluating DSA-based rectification processes for both line/space (L/S) and hexagonal contact hole (HEXCH) patterns printed with sub-optimal EUV conditions.
- For L/S patterns, the authors designed experiments at 28 nm and 24 nm pitch to assess defect rectification, while for HEXCH patterns, they investigated critical parameters such as local critical dimension uniformity (LCDU), ellipticity, and pattern placement error (PPE).
- Process variations, including block copolymer (BCP) formulation adjustments, film thickness changes, underlayer etch time, and additional annealing steps, were systematically studied to evaluate their influence on pattern fidelity. Furthermore, the team explored the potential of reducing EUV exposure dose by applying DSA rectification to low-dose patterns.

Results

- For 28 nm pitch L/S patterns: DSA healed most bridge defects; few dislocations remained; bubble defects appeared near wafer edges.
- For 24 nm pitch L/S patterns: Bridge defects were common, traced to polystyrene residues in the film. Reformulating the BCP reduced bridges by 3x.
- For 36 nm HEXCH patterns: LCDU improved from 2.26 nm (EUV resist) to 1.52 nm (DSA+etch); holes became more circular after etch; pattern placement error (PPE) increased, but was reduced with thicker BCP films and longer etch times.
- For 34 nm HEXCH patterns: DSA enabled ~60% EUV dose reduction while keeping LCDU and defectivity constant, overcoming the usual trade-off between dose and uniformity

Conclusions and References

- The study demonstrates that DSA can effectively mitigate stochastic variability in EUV lithography by "rectifying" noisy resist patterns into uniform structures. Benefits include improved LCDU, circularity of contact holes, and significant potential for EUV dose reduction.
- Challenges remain, bridge defects in L/S patterns and placement errors in HEXCH patterns. Future work focuses on new high-χ block copolymer materials and optimized process conditions to further enhance pattern fidelity and manufacturability.

- Verstraete, L. et al., "Mitigating stochastics in EUV lithography by directed self-assembly," Proc. SPIE Vol. 12497, 2023.
- Mack, C., "Metrics for stochastic scaling in EUV lithography," Proc. SPIE, 2019.- Ruiz, R. et al., "Density multiplication and improved lithography by directed block copolymer assembly," Science, 2008.
- Stoykovich, M. et al., "Remediation of line edge roughness in chemical nanopatterns by directed self-assembly," Macromolecules, 2010

Summary of the Self-assembly from milli- to nanoscales: methods and applications

- **Introduction:**
  - MEMS and nanodevices require integration of heterogeneous components.
  - Traditional pick-and-place assembly struggles at microscale:
  - Stiction, fragility, slow throughput
  - Self-Assembly (SA): Autonomous, parallel, scalable
- Advantages:
  - High throughput
  - Non-contact
  - Suitable for fragile or heterogeneous materials

SA of microelectromechanical structures

- Transform 2D planar parts into 3D microstructures
- Methods:
    - Thermal actuation
    - Polymer shrinkage
    - V-groove hinges
- Applications: Micro-robots, sensors, optical MEMS
- Compatible with standard planar fabrication processes

Capillary-Force Driven Assembly

- Uses surface tension to move and align components
- Techniques:
  - Folding 2D plates into 3D shapes
  - Capillary-driven placement on substrates
  - Simulation-guided optimization
- Advantages: Passive, parallel, precise alignment
- Examples: Water droplets guiding micro-parts

Shape Matching and Other-Directed Assembly Methods

- Components and receptor sites designed with complementary shapes
- Ensures passive self-alignment
- Advantages:
  - Selective capture of multiple part types
  - Reduces assembly errors
- Applications: Opto-electronic device integration, microstructure locking

Self-Assembly Using Magnetic Forces

- Non-contact actuation via magnetic forces
- Methods:
  - Patterned micromagnets on substrates
  - External magnetic fields
  - Magnetically functionalized parts
- Applications: Stepwise rotation and locking of hinged microstructures, 3D assembly
- Advantages: Reversible, scalable, allows out-of-plane rotation

Electric-Field Driven Self-Assembly

- Uses dielectrophoretic (DEP) to manipulate polarizable/charged parts
- Methods:
  - Electrodes create local field gradients
  - Selective movement based on polarizability
- Applications: Microchips, nanowires, carbon nanotubes
- Advantages: Precise, programmable, works in liquid environments
- Limitation: Requires conductive/polarizable parts

Colloidal Self-Assembly

- Sub-micron/µm particles form 2D or 3D ordered arrays
- Techniques: Convective assembly, Langmuir methods, confined evaporation
- Advantages: Parallel, self-limiting, scalable
- Applications: Colloidal crystals, functional nanomaterials

DNA-Based Self-Assembly

- DNA strands act as scaffolds or selective linkers
- DNA origami folds nanoscale components into programmable shapes
- Advantages: High selectivity, nanoscale precision, parallel assembly
- Applications: Nanoscale electronics, sensors, micro-robots

Advantages of Self-Assembly

- Parallel and scalable → high throughput
- Non-contact → safe for fragile components
- Compatible with heterogeneous materials
- Can create 3D structures from 2D planar parts
- Adaptable from millimeter to nanometer scales

Limitations and challenges

- Depends on specific forces: capillary, magnetic, electric, DNA binding
- Requires careful material selection and surface design
- Magnetic/electric methods may have interference issues
- Precision depends on field design and process control

Conclusion

- Self-assembly offers a versatile, scalable alternative to traditional pick-and-place
- Different forces are suited to different scales and materials
- Enables high-throughput integration of MEMS/NEMS components
- Promising route for future complex micro- and nano systems

Thank you

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