# Polymer-Assisted Nanofabrication for Advanced Nano-Optical Manufacturing: From Electron Beam Resist Engineering to Scalable Metalens Fabrication

## A Review of Advances in Polymer-Assisted Nanofabrication, High-Aspect-Ratio Structuring, and Emerging Metasurface Manufacturing

**R. K. Dey**

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## Abstract

The rapid evolution of nanoscale device architectures for photonics, nanoelectronics, sensing, and advanced microscopy has placed increasingly stringent demands on nanofabrication methodologies. Over the past decade, innovations in electron beam lithography (EBL), resist engineering, high-aspect-ratio silicon processing, and nanoscale transfer methodologies have substantially expanded achievable fabrication resolution, throughput, and structural complexity. This review presents a comprehensive examination of advances spanning polymer resist physics, self-developing and grafted resist systems, nanoscale silicon etching, atomic force microscopy (AFM) probe manufacturing, nano-Schottky device fabrication, antireflective nanostructures, and emerging metalens manufacturing techniques. Particular emphasis is placed on the convergence of process innovations that enable scalable manufacturing of next-generation nano-optical devices. The review further discusses how foundational developments in EBL process control have evolved into practical routes toward metasurface and metalens fabrication, establishing a pathway toward future photonic computing and compact optical systems.

**Keywords:** Electron beam lithography, grafted polymer resist, nanofabrication, metalens, metasurface manufacturing, AFM probe, silicon nanostructures, photonic devices

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# 1. Introduction

Nanofabrication has emerged as a cornerstone of modern microelectronics, photonics, and nanoscale sensing technologies. The relentless push toward smaller dimensions and more complex three-dimensional architectures has exposed significant limitations in conventional lithographic techniques, particularly in resist performance, pattern fidelity, substrate conformity, and scalability.

Electron beam lithography remains one of the most versatile tools for sub-10 nm patterning. However, its industrial translation has historically been limited by issues including:

- stitching errors
- resist sensitivity limitations
- substrate topography incompatibility
- poor adhesion
- difficult lift-off processes
- low throughput

A substantial body of research over the last decade has addressed these limitations through innovations in polymer chemistry, process integration, and nanoscale etching strategies.

This review synthesizes advances across these domains and identifies a coherent technological trajectory toward scalable fabrication of advanced photonic structures such as metalenses and nano-optical interfaces.

# 2. Evolution of Electron Beam Resist Engineering

## 2.1 Early Advances in Self-Developing Resist Systems

A critical milestone in EBL process optimization was the development of **self-developing resist mechanisms** for in-situ process feedback.

Dey and Cui demonstrated **electron beam lithography with feedback using in situ self-developed resist**, enabling direct process correction during patterning and significantly reducing write-field errors [16].

This work was extended to stitching error reduction using self-developing resist systems, demonstrating substantial improvements in large-area pattern continuity [18].

These innovations introduced a process-monitoring paradigm that significantly improved deterministic nanoscale fabrication.

## 2.2 Polystyrene as a High-Sensitivity EBL Resist

Traditional PMMA resist systems are constrained by sensitivity-performance tradeoffs.

Con et al. demonstrated that **high molecular weight polystyrene** exhibits exceptional sensitivity as an electron beam resist [19].

Subsequent work by Dey et al. examined the influence of molecular weight distribution on exposure characteristics [17], showing that resist polydispersity strongly affects:

- contrast
- line edge roughness
- development kinetics

This represented a significant contribution to polymer resist optimization.

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## 2.3 Tunable Hybrid Resist Architectures

Zheng et al. introduced mixtures of **ZEP and PMMA** with tunable sensitivity and controllable undercut profiles [13].

These systems enabled tailored resist performance for lift-off applications while preserving nanoscale resolution.

The significance of this work lies in demonstrating that resist behavior can be systematically engineered through compositional tuning.

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# 3. Grafted Polymer Brush Lithography

## 3.1 PMMA Brush for Irregular Surface Lithography

Conformal lithography over non-planar surfaces remains a major challenge.

Dey et al. introduced **surface-grafted PMMA brush layers** for EBL on irregular substrates [1].

This work demonstrated:

- improved surface conformity
- enhanced adhesion
- reduced collapse
- better pattern transfer on topographically complex substrates

This was among the earliest demonstrations of practical conformal EBL on irregular surfaces.

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## 3.2 Negative Tone Surface-Grafted PMMA

Yamada et al. established that single-layer surface-grafted PMMA can function as an effective negative-tone resist [2].

This introduced simplified process architectures with:

- fewer coating steps
- improved pattern robustness
- reduced interface instability

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## 3.3 Dual-Tone Polystyrene Brush Systems

Aydinoglu et al. further expanded this concept through grafted polystyrene monolayer brushes exhibiting both positive and negative tone behavior [3].

Such dual-tone functionality enables highly flexible pattern design strategies.

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## 3.4 Enhanced Adhesion via Copolymer Brushes

Francesco et al. demonstrated enhanced adhesion using grafted PMMA-co-methacrylic acid brushes [14].

Adhesion engineering is particularly important for:

- multilayer processing
- aggressive etching
- high-aspect-ratio transfer

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# 4. Advances in Lift-Off and Pattern Transfer

Lift-off remains central to nanoscale metal patterning.

Dey and Cui introduced **solvent-assisted lift-off for negative resist systems under low-energy exposure** [15], significantly improving process reliability.

This approach enabled:

- lower thermal budget
- reduced resist damage
- improved metal edge definition

Such methods remain highly relevant for plasmonic and photonic nanostructures.

# 5. Silicon Nanostructure Fabrication

## 5.1 Conductivity-Controlled Undercut Engineering

Dey, Ekinci, and Cui demonstrated that mask conductivity strongly affects lateral undercut etching in silicon nanopillar fabrication [4].

This revealed an important electrochemical mechanism governing anisotropic etching behavior.

## 5.2 Two-Step KOH Etching

Ekinci et al. developed a **two-step KOH etching process** for enhanced trench aspect ratio [6].

The method provides superior geometric control for:

- MEMS structures
- photonic trenches
- microfluidic interfaces

## 5.3 Oxidation Sharpening of Silicon Tips

Dey et al. demonstrated atmospheric oxidation sharpening for silicon tip fabrication [10].

This low-complexity route enables ultra-sharp tip generation suitable for:

- AFM probes
- field emitters

- nano-contact devices

# 6. AFM Probe Manufacturing Innovations

AFM probe fabrication has benefited significantly from process advances.

Zheng et al. reported **batch fabrication of AFM probes with direct positioning capability** [11].

Samaana et al. later demonstrated focused ion beam milled etch masks for high-aspect-ratio AFM probes [5].

Together, these approaches improved:

- tip precision
- batch scalability
- mechanical robustness

These methods are directly relevant to next-generation nanoscale characterization tools.

# 7. Nanoelectronic Device Fabrication

Nano-Schottky contacts represent a unique intersection of fabrication precision and electronic transport physics.

Rezeq et al. theoretically and experimentally investigated nano-Schottky contacts [8].

Subsequent work quantified probe-size dependence in Schottky junction I–V characteristics [9].

These studies established critical scaling laws for nanoscale contact engineering.

# 8. Nano-Optical Surface Engineering

## 8.1 Moth-Eye Antireflective Nanostructures

Liu et al. demonstrated moth-eye antireflection nanostructures on glass for CubeSat applications [7].

The work showed:

- broadband reflection suppression
- environmental robustness
- scalability

This represented an important bridge between nanofabrication process development and practical optical deployment.

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# 9. Transition Toward Metasurface and Metalens Manufacturing

Recent patent developments demonstrate a clear transition from foundational nanofabrication research toward scalable metasurface manufacturing.

These include:

- microscale structure fabrication [Patent 7]
- metalens manufacturing methods [Patents 6, 8]

The transition is technologically significant because metalens fabrication requires:

- subwavelength precision
- large-area pattern fidelity
- repeatable nanoimprint transfer
- defect minimization

The earlier advances in:

- resist engineering
- irregular surface patterning
- undercut control
- nanoscale transfer optimization

provide precisely the process foundation needed for practical metalens manufacturing.

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# 10. Industrial Translation and Future Opportunities

The reviewed body of work suggests several future directions:

## 10.1 Scalable Nanoimprint Metalens Manufacturing

Combining stamp-based transfer with optimized resist systems could enable wafer-scale metasurface production.

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## 10.2 Photonic AI Hardware

Nanofabrication methodologies developed for optical structures are directly relevant to:

- photonic neural accelerators
- optical interconnects
- edge AI photonics

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## 10.3 Quantum and Sensing Applications

High-aspect-ratio nanoscale structures offer opportunities in:

- quantum photonics
- biosensing
- nonlinear optics

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# 11. Conclusion

Over the past decade, nanofabrication research has progressed from incremental process optimization to enabling entirely new device classes.

Advances reviewed here demonstrate a coherent technological evolution:

**self-developing resist systems → grafted polymer lithography → advanced silicon etching → nanoscale probe fabrication → nano-optical surface engineering → scalable metasurface manufacturing**

This progression establishes a robust foundation for next-generation photonic and nanoelectronic systems.

The integration of polymer science, process engineering, and device fabrication continues to define the future of scalable nanoscale manufacturing.

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