Title

Navigating the research landscape for hyper-NA EUV lithography and future patterning technologies

Journal

Proceedings of SPIE--the International Society for Optical Engineering, 13686

ISSN

0277-786X

Authors

La Fontaine, Bruno

Rekawa, Senajith

Miyakawa, Ryan

et al.

Publication Date

2025-11-06

DOI

10.1117/12.3074981

Invited Paper

Navigating the Research Landscape for Hyper-NA EUV Lithography and Future Patterning Technologies

Bruno La Fontaine[1*], Senajith Rekawa[1], Ryan Miyakawa[1], Warren Holcomb[1], Markus Benk[1], Oleg Kostko[1], Cheng Wang[1,3], Qi Zhang[1], Eric Gullikson[1], Weilun Chao[1], Mi-Young Im[1], Dmytro Zaytsev[1], Frances Houle[4], Brett Helms[3], Paul Nealey[5,6], Chris Ober[6], and Ricardo Ruiz[3]

[1] Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, California, USA

[2] The Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, California, USA

[3] Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California, USA

[4] Chemical Sciences Division and Molecular Biophysics and Integrated Bioimaging Division, Berkeley, California, USA

[5] Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637

[6] Argonne National Laboratory, Material Science Division, Lemont, Illinois 60439

[7] Department of Materials Science and Engineering, Cornell University, Ithaca, New York 14853, USA

* corresponding author: blafontaine@lbl.gov

ABSTRACT

Hyper-Numerical Aperture (Hyper-NA) Extreme Ultraviolet (EUV) lithography is gathering growing support as the technology of choice to sustain the dimensional scaling trajectory of Moore's Law. This transition, which targets resolution down to 5 nm, necessitates several research advances across several key lithography areas, such as patterning materials, imaging with polarization control, and the optimization of the mask structure. In this paper, we briefly review the historical role of the government-industrial partnerships enabling Center for X-Ray Optics (CXRO) pathfinding research for prior EUV lithography generations. We also highlight the role of the Department of Energy's Energy Frontier Research Center (EFRC) on High-Precision Patterning Science (CHiPPS) as a critical initiative to fundamentally address the pervasive stochastic challenges in materials science that limit the RLS (Resolution, Sensitivity, Line Edge Roughness) tradeoff, charting a path toward the Angstrom Era. We then provide a perspective of the research and next generation of infrastructure, such as the Hyper-NA MET, which is needed to enable the patterning of ~5 nm half-pitch features.

1. THE IMPORTANCE OF RESEARCH INVESTMENTS FOR CONTINUED 2D SCALING

It is well known that the time required for lithography solutions to mature from commercial lithography tool prototypes in industrial research settings (such as IMEC[1]or Albany Nanotech[2]) to High-Volume Manufacturing (HVM) is significant, with EUV lithography requiring approximately 13 years compared to 9 years for ArF and another 3 years for immersion lithography.[3]

Just as important is the effort that takes place before commercial tools become available, when supporting materials and technologies are being developed. Nearly 20 years elapsed between the first papers on soft x-ray lithography[4-6] and the availability of a commercial EUV tool (ASML's Alpha Demo Tool)[7]. During that time, the EUV LLC[8] established a partnership between the industry and US National Labs to break down scientific and technological barriers to the insertion of EUV lithography. After that, the SEMATECH[9] consortium invested heavily in the development of EUV infrastructure, partnering with Berkeley Lab, again with the goal to enable its insertion in high-volume manufacturing (HVM). These efforts led to many important advances that enabled many aspects of EUV lithography infrastructure: micro-exposure tools (MET3, a 0.3NA EUV tool) demonstrating patterning capabilities[10-12], actinic interferometry[13-14] (e.g., on the ETS and on METs), and mask review microscopes[15-16] (AIT, SHARP). This period of intense research led to many significant advances in patterning materials and the access to the highest resolution capabilities of MET3 was key in identifying and quantifying the imaging improvements afforded by metal-oxide-based resists.[12] It also provided much of the early learning on mask defect printability.[17] The development and adoption of each generation of EUV lithography

International Conference on Extreme Ultraviolet Lithography 2025, edited by Toshiro Itani, Kurt G. Ronse, Patrick P. Naulleau, Paolo A. Gargini, Proc. of SPIE Vol. 13686, 136861E · 2025 Published by SPIE · 0277-786X · doi: 10.1117/12.3074981

have relied heavily on research infrastructure capable of providing core imaging capabilities well ahead of commercial scanner availability. CXRO at Lawrence Berkeley National Laboratory (LBNL) has continuously served this function through its series of Micro-Exposure Tools (METs), hosted at the Advanced Light Source (ALS).

1.1 The EUREKA Program and MET5

A more recent example is that of the EUREKA program, another government-industry partnership founded jointly by Intel, tsmc, Samsung and Berkeley Lab in 2016, which enabled the design, fabrication, and operation of MET5 (0.5NA micro-exposure tool).[18] During a period of about 6 years between the first prints on MET5 and the delivery of the first ASML high-NA EUV scanner, over a thousand different patterning materials were evaluated on this tool at Berkeley. Such an effort enabled the rapid integration of high-NA EUV into chipmakers' development and manufacturing lines.[19]

The EUREKA program with CXRO provided a crucial platform for the development of high-NA EUV technology, particularly in validating the performance of new resists and mask designs, demonstrated by patterning down to 7.5 nm half-pitch features on MET5, as illustrated in Figure 1., which shows a typical print of 7.5 nm lines on a 15 nm pitch in a metal organic resist. The measured LER typically measured on such features is around 2nm.

Key performance indicators achieved on the MET5 include:

- Imaging Quality: The full MET5 platform affords very high contrast (>70%) at high resolution (beyond 20-nm pitch), fundamentally supported by a set of projection optics with an RMS wavefront error of 0.31 nm (lambda/44) and system flare below 2%, but also by controlling vibrations to the nm level and maintaining temperature variations within a tenth of a millikelvin.
- Resist Optimization: Experimental work on 0.55 NA demonstrated that the introduction of new resist platforms substantially improved Dose-to-Size (DtS) and Line Edge Roughness (LER), a necessary step for high-volume manufacturing.

In addition to lithographic printing on MET5, some fundamental work on photoresists have established foundational characterization of photo- and secondary-electron yield, electron ranges in materials and the identification of chemistry directly induced during EUV exposure, prior to post-exposure bake.[20-23]

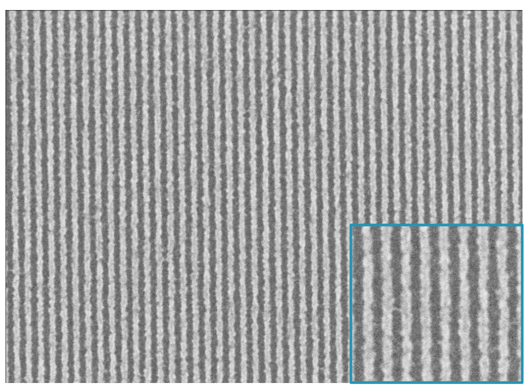

Figure 1 – Lithography print from MET5 using a metal-organic resist, showing 7.5nm lines and spaces (pitch = 15nm) and a LER on the order of 2nm, illustrating typical capabilities of this tool using metal-organic resists.

Also of significant importance is the first experimental validation of anamorphic imaging at 0.55NA, on the SHARP reticle imaging microscope, years before any other tool could even attempt this validation work.[24]

1.2 The Center for High-Precision Patterning Science (CHiPPS)

CHiPPS, a DOE funded Energy Frontiers Research Center, is a foundational research initiative dedicated to establishing comprehensive knowledge and control over the complex chemical and physical processes governing nanoscale pattern formation.[25] The Center's primary objective is to achieve fundamental understanding of the mechanisms leading to atomically precise patterning while addressing stochastic variations, establishing CHiPPS as a unique research center for comprehensive knowledge on patterning science.

The EUV process, involving photoresist exposure, post-exposure bake, development, and pattern transfer, is complicated by the ionizing effects of EUV radiation, which demands precise control over material absorption and subsequent chemical transformations. CHiPPS addresses these challenges through four integrated research thrusts: Patterning Materials, Hierarchical Materials, Theory and Modeling, and Characterization. The following summarizes key advancements achieved so far.

To advance the efficiency and control of EUV patterning, CHiPPS is synthesizing molecularly precise material platforms to optimize the spatial relationship between EUV-absorbing species and chemical functionalities.

- Sequence-Defined Polypeptoids[26]: Significant progress has been achieved in molecularly tailored resists. Researchers successfully developed positive-tone peptoid resists, establishing a minimum chain length ~ 20 mers required for solubility contrast. Furthermore, the synthesis of negative-tone polypeptoid resists achieved 14nm half-pitch resolution, with outgassing studies indicating that EUV-triggered reaction is the mechanism for solubility switching.
- Metal-Organic Dry Resists and Perovskites: Efforts to enhance EUV absorption and sensitivity focused on optimizing bond connectivity and incorporating high atomic number metals. In metal-organic dry resists (e.g., alucone variants), lower crosslink density was found to boost sensitivity, enabling patterning down to 14nm.[27] Concurrently, the metal-halide perovskite platform was validated as a high-yield source of low-energy electrons, confirming their strong potential as novel EUV-sensitive materials.

CHiPPS also investigates how hierarchical materials with inherent molecular uniformity can mitigate stochastic variations. The development of A-b-(B-r-C) block copolymers yielded self-assembled structures with 24-28 nm full pitch, suitable for integration with positive-tone and negative-tone High-NA EUV exposure. Resonant Soft X-ray Scattering (RSoXS) confirmed that these novel high-χ, low-N block copolymers exhibit exceptionally sharp interfaces, suggesting superior thermodynamic properties for directed self-assembly (DSA) platforms.

In pattern transfer, a new area-selective deposition method using polypeptoid brushes as growth promoters for Atomic Layer Deposition (ALD) was successfully demonstrated. Functional peptoids enabled the rapid formation of AlOx hardmasks with growth rates five times faster than conventional ALD.

These material advancements are supported by sophisticated computational and characterization efforts. These include modeling with a full computational workflow for kinetics prediction, as well as the development of a reaction network discovery tools and applying machine-learned interatomic potentials (MLIPs) to predict reaction free energies efficiently, significantly accelerating the construction of full resist radiolysis models. Multimodal characterization has yielded key physical parameters, such as electron attenuation length (EAL) measurements, which show that electron interactions are dominated by material composition rather than energy in the 10–90 eV range. This integrated approach, which includes advanced outgassing monitoring with Picarro, Inc. and nanoscale latent image analysis with RSoXS, is providing the essential validation data required to bridge the gap between fundamental chemistry and lithographic pattern fidelity.

2. RESEARCH FOR THE FUTURE OF EUV LITHOGRAPHY: THE HYPER-NA MET LAB AND BUILDING UPON THE CHiPPS RESEARCH CENTER

The Hyper-NA MET Lab is designed to push the boundaries of resolution, imaging control, and metrology capabilities to validate the next wave of process technologies and semiconductor device science. This Lab should comprise a micro-exposure lithography tool, a set of instruments for the characterization and metrology of resist materials using soft x-rays as a probe, a holographic lithography tool that will provide early access to imaging using controllable polarized-light illumination, and a Hyper-NA EUV mask imaging microscope.

2.1 The Hyper-NA EUV Micro-Exposure Tool

To address the 0.75 NA node (targeting pitches down to 10 nm), the development of next-generation Hyper-NA MET needs to be accelerated, which requires a strong government-industry commitment.

The proposed tool will include several significant technological improvements, as indicated in Table 1. Resolution of 5nm lines on a 10nm pitch with better than 85% contrast represents a 33% improvement in resolution at the same or better image contrast, relative to MET5. The addition of full polarization control will enable early assessment of its importance for the future Hyper-NA commercial tools, especially for 2D patterns on irregular pitches. The >2× increase in throughput will lead to the ability to test more patterning materials and faster learning. Combined with the alignment capability, this will also enable research on advanced materials and novel devices for the future of microelectronics.

Parameter	Current MET5 (0.5NA)	Hyper-NA MET (0.75NA) Target
Resolution	down to 7.5 nm	down to 5 nm
Throughput	>10 wafers per day	> 2× increase
Wafer Size	200 mm	200mm & 300 mm capable
Polarization	Fixed	Full sector-polarization control
Overlay	No	1nm alignment capability

Table 1 – Main differences between the proposed Hyper-NA MET and MET5.

The successful deployment of this tool hinges on overcoming extreme mechanical and optical stability challenges. Scaling lithography to NA=0.75 imposes strict requirements on dynamic system performance and materials response. The move from 0.55 NA to 0.75 NA requires a 3× improvement in overall mechanical stability to maintain adequate image contrast. The Hyper-NA system has a target of ~0.35 nm rms for stability of the image on the wafer during exposure (with individual components such as wafer stage vibrations targeting ≲0.3 nm rms) to maintain a minimum NILS of 2.0 at the 10nm pitch. The Hyper-NA MET is engineered to meet these demanding targets, necessitating advanced staging systems for the reticle and wafer with highly precise positioning control.

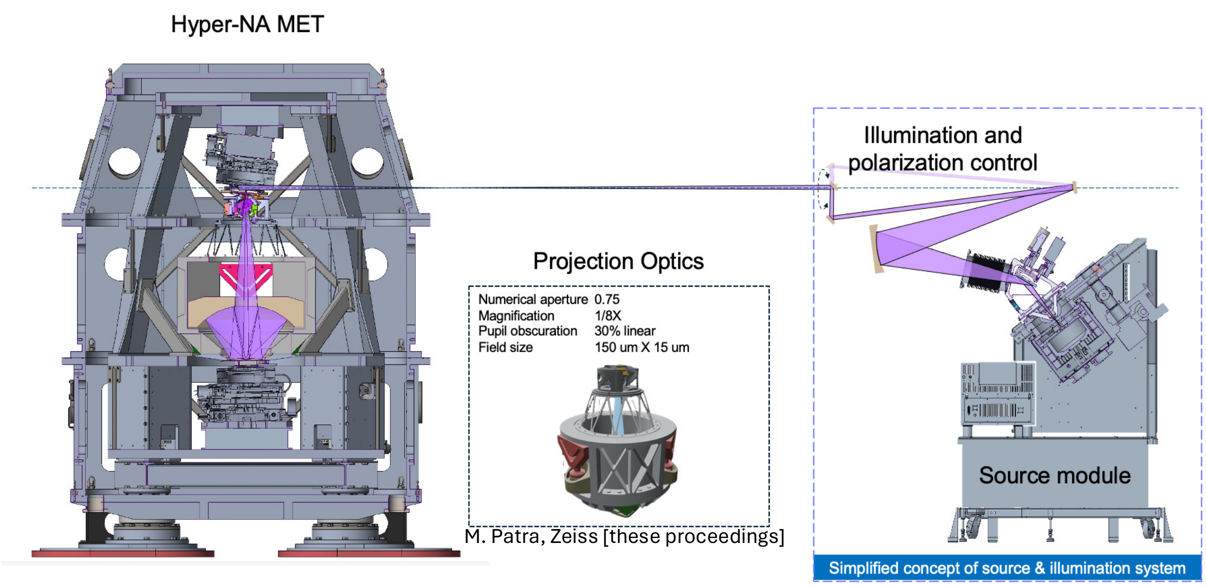

Figure 2 – Conceptual description of the proposed Hyper-NA micro-exposure tool, showing a cross-section of the platform with the optics, reticle, and wafer stages, as well as the metrology frame. A stand-alone plasma source is envisaged, together with polarization-controlling optics, to provide sector-polarization illumination of the mask. The numerical aperture of the proposed projection optics[28] is 0.75, with a de-magnification of 1/8✕, a central obscuration of 30% (linear) and a field size of 15µm by 150µm.

2.2 Hyper-NA Mask Imaging Microscope

A Hyper-NA EUV mask imaging microscope is needed to enable early studies of the influence of mask architecture on the image NILS and the imaging depth of focus, which are key parameters to fully understand the extendibility of EUV lithography. The imaging depth-of-focus is identified as one of the top issues hindering broader adoption of high-NA EUV lithography and possibly blocking the insertion of Hyper-NA EUV.

The SHARP microscope has already demonstrated mask-side Hyper-NA imaging, as shown in Figure 3.[29]

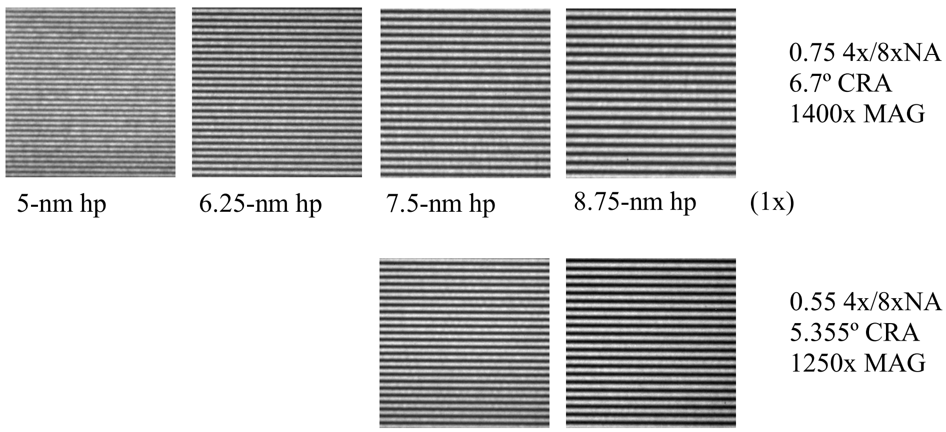

Figure 3 – First images of an EUV mask using Hyper-NA an off-axis diffractive optics (Fresnel zone plate - FZP) compared to images taken with a high-NA FZP. Patterns with lines and spaces smaller than 7.5nm half-pitch could not be resolved with a high-NA lens but were clear with a Hyper-NA lens.

While much progress has been achieved through source-mask optimization approaches[30], including sub-resolution assist features and other diffractive mask sub-structures[31] and control of the lithography lens aberrations, we believe that the fundamental architecture of the mask should be studied more broadly. This could include a modification of the multilayer film itself, through programmed variable duty-cycle multilayers, known as aperiodic multilayers[32], or a different arrangement of the 'absorbing' patterns on the mask, such as by etching the multilayers or etching and filling the multilayer film locally to create a patterned contrast on the mask. Our early simulation results, displayed in Figure 4, indicate that there could be significant gains in both NILS and DOF using such approaches. We note here however that we did not perform proper source-mask optimization for these simulations, given that the infrastructure for such a task does not exist currently. These are just examples, and we are not suggesting that these architectures should be adopted but rather that a broader view of the problem is warranted given the potential gains: a larger process window with a higher NILS (which translates into lower LER and a larger defect-free window) can provide better yield thus reducing cost-of-ownership.

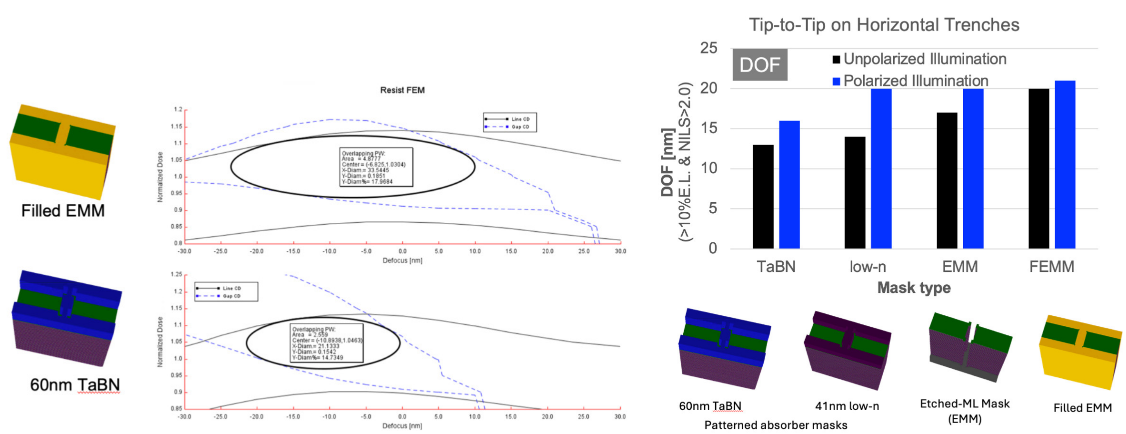

Figure 4 –Simulations of imaging performance comparing different mask architectures. A standard mask using a 60nm thick TaBN absorber is compared to a low-n mask with a 41nm absorber and to an etched-multilayer mask (EMM) and to a filled-EMM (FEMM). There are clear differences in the simulated process windows (left side) and the NILS-limited DOF, indicating that mask architecture can have a strong influence on process capability, including defect-free windows, which should be studied.

3.2. A Continued and Augmented Effort on the Fundamental Science of Patterning Materials

The path toward developing resists satisfying the patterning requirements for Hyper-NA EUV lithography has been identified as the most critical research topic to enable a transition from the Lab to a commercial lithography tool operating in an industrial pilot line.

As such, it is imperative that a research center such as CHiPPS continue to receive strong support, to continue addressing the resolution-LER-sensitivy (RLS) challenge, with strong contributions and guidance from industry. At the moment, CHiPPS is the only research center with such a comprehensive focus on patterning science that groups leading experts and capabilities from materials synthesis to patterning, characterization, and modeling.

Based on its learning so far and on the capabilities that it has established on materials synthesis sequencing and control of materials composition, it is ideally positioned to establish foundational knowledge on the effect of these parameters on LER and defectivity. For instance, sequence-defined polypeptoids and molecular-layer deposited materials can now be used in conjunction with ultimate-resolution EUV patterning capabilities and some of the most advanced soft x-ray-based characterization instrumentation to study such effects. The CHiPPS Center is also poised to start addressing the influence of underlayers and explore the fundamentals of dry resists.

In addition, the recent achievements in the understanding of the role of block copolymer interfacial width and the fundamental thermodynamic properties of directed self-assembly (DSA) provide a path to control line-width roughness and CD uniformity at the extreme resolution afforded by Hyper-NA EUV lithography. The A-b-(B-r-C) BCP architecture has already achieved EUV-relevant morphologies down to 4-nm half-pitch.

Finally, the development of advanced soft x-ray characterization techniques such as RSoXS and RSoXR provide a path to probing chemistry in resists with sub-nm resolution, before development. Coupled with theory and modeling based on MLIP, capable of accelerating the research on full resist radiolysis models, this provides world-leading capabilities essential to accelerate the research on the future scaling of EUV lithography.

3. CONCLUSION

The transition to Hyper-NA EUV lithography is technically challenging but essential to continued 2D scaling. LBNL's long-standing institutional commitment, demonstrated by the successful operation of the MET systems and research on patterning materials, needs to continue with the development of a Hyper-NA MET lab targeting feature sizes down to 5nm. This infrastructure, coupled with the fundamental scientific exploration provided by an augmented continuation of the CHiPPS EFRC, forms a robust research landscape, unique worldwide, that is necessary to address the immense challenges in material sciences, EUV imaging, soft x-ray science and modeling. This will ensure the continuity of dimensional scaling into the next decade and address a critical aspect of the increasing demand for energy-efficient chips for AI.

ACKNOWLEDGMENTS

Part of this work was supported as part of the Center for High Precision Patterning Science (CHiPPS), an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231.

Other parts of this work was supported through contracts with industrial and other strategic partners that are members of the EUREKA program.

REFERENCES

1. https://www.imec-int.com/en

2. https://ny-creates.org/about/albany-nanotech-complex/

3. Luciana Meli, Indira Seshadri, Jed Rankin, Jennifer Church, Yasiel Cabrera, Christopher Penny, Jaime Morillo, Stuart Sieg, Dario Goldfarb, Nicholas Latham, Teresa Howe, Joe Lee, Yann Mignot, Scott Halle, "Accelerating high-NA EUV

lithography insertion for interconnect scaling and beyond: Performance, cost, and future prospects," Proc. SPIE PC13424, Optical and EUV Nanolithography XXXVIII, PC134240J (23 April 2025) https://doi.org/10.1117/12.3056559

4. H.Kinoshita, T.Kaneko, H.Takei, N.Takeuchi, and S.Ishihara, In Conf. of Appl. Phys., (28p-zf 15, Jpn. Soc. Appl. Phys. 1986)

5. Andrew M. Hawryluk, and Lynn G. Seppala. "Soft x-ray projection lithography using an x-ray reduction camera." Journal of Vacuum Science & Technology B, vol. 6, no. 6, 1988, pp. 2162-2166, https://doi.org/10.1116/1.584107.

6. J. E. Bjorkholm, J. Bokor, L. Eichner, R. R. Freeman, J. Gregus, T. E. Jewell, W. M. Mansfield, A. A. Mac Dowell, E. L. Raab, W. T. Silfvast, L. H. Szeto, D. M. Tennant, W. K. Waskiewicz, D. L. White, D. L. Windt, O. R. Wood, II, and J. H. Bruning, Journal of Vacuum Science & Technology B in November 1990. https://doi.org/10.1116/1.585106.

7. Hans Meiling, Vadim Banine, Noreen Harned, Brian Blum, Peter Kuerz, Henk Meijer, "Development of the ASML EUV alpha demo tool," Proc. SPIE 5751, Emerging Lithographic Technologies IX, (6 May 2005) https://doi.org/10.1117/12.600725

8. Chuck Gwyn and Stefan Wurm, “EUV LLC: An Historical Perspective”, in EUV Lithography, Vivek Bakshi editor, SPIE (2008) https://doi.org/10.1117/3.769214.ch2

9. https://en.wikipedia.org/wiki/SEMATECH

10. Patrick Naulleau, Kenneth A. Goldberg, Erik H. Anderson, Kevin Bradley, Rene Delano, Paul Denham, Bob Gunion, Bruce Harteneck, Brian Hoef, Hanjing Huang, Keith Jackson, Gideon Jones, Drew Kemp, James Alexander Liddle, Ron Oort, Al Rawlins, Senajith Rekawa, Farhad Salmassi, Ron Tackaberry, Carl Chung, Layton Hale, Don Phillion, Gary Sommargren, John Taylor, "Status of EUV micro-exposure capabilities at the ALS using the 0.3-NA MET optic," Proc. SPIE 5374, Emerging Lithographic Technologies VIII, (20 May 2004); https://doi.org/10.1117/12.556538

11. Patrick P. Naulleau, Christopher N. Anderson, Jerrin Chiu, Kim Dean, Paul Denham, Kenneth A. Goldberg, Brian Hoef, Sungmin Huh, Gideon Jones, Bruno M. LaFontaine, Andy Ma, Dimitra Niakoula, Joo-on Park, Tom Wallow, "Advanced extreme ultraviolet resist testing using the SEMATECH Berkeley 0.3-NA microfield exposure tool," Proc. SPIE 6921, Emerging Lithographic Technologies XII, 69213N (3 April 2008); https://doi.org/10.1117/12.773833

12. Patrick Naulleau, Christopher N. Anderson, Lorie-Mae Baclea-an, David Chan, Paul Denham, Simi George, Kenneth A. Goldberg, Brian Hoef, Gideon Jones, Chawon Koh, Bruno La Fontaine, Brittany McClinton, Ryan Miyakawa, Warren Montgomery, Seno Rekawa, Tom Wallow, "The SEMATECH Berkeley MET pushing EUV development beyond 22nm half pitch," Proc. SPIE 7636, Extreme Ultraviolet (EUV) Lithography, 76361J (22 March 2010); https://doi.org/10.1117/12.848438

13. Patrick P. Naulleau, Kenneth A. Goldberg, Sang Hun Lee, Chang-Hasnain C. Chang, Phillip J. Batson, David T. Attwood Jr., Jeffrey Bokor, "Recent advances in EUV phase-shifting point diffraction interferometry," Proc. SPIE 3767, EUV, X-Ray, and Neutron Optics and Sources, (23 November 1999); https://doi.org/10.1117/12.371113

14. Kenneth A. Goldberg, Patrick Naulleau, Paul Denham, Senajith B. Rekawa, Keith Jackson, James Alexander Liddle, Erik H. Anderson, "EUV interferometric testing and alignment of the 0.3-NA MET optic," Proc. SPIE 5374, Emerging Lithographic Technologies VIII, (20 May 2004); https://doi.org/10.1117/12.546199

15. Kenneth A. Goldberg, Patrick P Naulleau, Anton Barty, Senajith B. Rekawa, Charles D. Kemp, Robert F Gunion, Farhad Salmassi, Eric M. Gullikson, Erik H. Anderson, Hak-Seung Han M.D., "Performance of actinic EUVL mask imaging using a zoneplate microscope," Proc. SPIE 6730, Photomask Technology 2007, 67305E (30 October 2007); https://doi.org/10.1117/12.746756

16. Kenneth A. Goldberg, Iacopo Mochi, Markus Benk, Arnaud P. Allezy, Michael R. Dickinson, Carl W. Cork, Daniel Zehm, James B. Macdougall, Erik Anderson, Farhad Salmassi, Weilun L. Chao, Vamsi K. Vytla, Eric M. Gullikson, Jason C. DePonte, M. S. Gideon Jones, Douglas Van Camp, Jeffrey F. Gamsby, William B. Ghiorso, Hanjing Huang, William Cork, Elizabeth Martin, Eric Van Every, Eric Acome, Veljko Milanovic, Rene Delano, Patrick P. Naulleau, Senajith B. Rekawa, "Commissioning an EUV mask microscope for lithography generations reaching 8 nm," Proc. SPIE 8679, Extreme Ultraviolet (EUV) Lithography IV, 867919 (1 April 2013); https://doi.org/10.1117/12.2011688

17. I. Mochi, K. A. Goldberg, B. La Fontaine, A. Tchikoulaeva, C. Holfeld, "Actinic imaging of native and programmed defects on a full-field mask," Proc. SPIE 7636, Extreme Ultraviolet (EUV) Lithography, 76361A (20 March 2010); https://doi.org/10.1117/12.846670

18. Ryan H. Miyakawa, Wenhua Zhu, Geoff Gaines, Chris Anderson, Patrick Naulleau, "Berkeley MET5 update: commissioning, interferometry, and first prints (Conference Presentation)," Proc. SPIE 10809, International Conference on Extreme Ultraviolet Lithography 2018, 1080911 (12 October 2018); https://doi.org/10.1117/12.2501953

19. Florian Gstrein, "Hyper-NA EUV Lithography: A Chipmaker's Perspective", 2nd International Workshop on Hyper-NA EUV Lithography, Pacific Grove, CA (October 2025)

20. Kostko, O., McAfee, T. R., Ma, J. H., Blackwell, J. M., & Naulleau, P. (2024). Experimental characterization of model extreme ultraviolet resist materials. Journal of Micro/Nanopatterning, Materials, and Metrology, 23(1), 014602.

21. Mueller, M., McAfee, T., Naulleau, P., Oh, D., & Kostko, O. (2024). Study of electron-induced chemical transformations in polymers. *Journal of Micro/Nanopatterning, Materials, and Metrology*, *23*(4), 041403. https://doi.org/10.1117/1.JMM.23.4.041403

22. Oleg Kostko, Maximillian Mueller, Patrick Naulleau, Evaluation of Electron Blur for Different Electron Energies, Journal of Photopolymer Science and Technology, 2024, Volume 37, Issue 3, Pages 315-320 2004 https://doi.org/10.2494/photopolymer.37.315

23. P. O'Reilly, B. Yu, W. Holcomb, A. Sumitro, R. Ruiz, B. La Fontaine, C. Wang, L. McQuade, M. Bhattacharya, S. Castellanos, S. Park, and Qi Zhang*. J. Micro/Nanopattern. Mater. Metrol. 24(2), 024002 (2025). https://doi.org/10.1117/1.JMM.24.2.024002.

24. Markus P. Benk, Antoine Wojdyla, Weilun Chao, Farhad H. Salmassi, Sharon R. Oh, Yow-Gwo Wang, Ryan H. Miyakawa, Patrick P. Naulleau, Kenneth A. Goldberg, "Emulation of anamorphic imaging on the SHARP extreme ultraviolet mask microscope," J. Micro/Nanolith. MEMS MOEMS 15(3) 033501 (12 July 2016) https://doi.org/10.1117/1.JMM.15.3.033501

25. https://chipps.lbl.gov/

26. Cameron P. Adams, Carolyn Henein, Xiangxi Meng, Chenyun Yuan, Javier Read de Alaniz, Christopher K. Ober, and Rachel A. Segalman, "Polymer Sequence Alters Sensitivity and Resolution in Chemically Amplified Polypeptoid Photoresists", ACS Macro Letters 2025 *14* (8), 1055-1059 https://doi.org/10.1021/acsmacrolett.5c00320

27. L. V. Than, G. D'Acunto, M. Harake, H. Im, O. Kostko, S. F. Bent. *ACS Appl. Mater. Interfaces.* 2025, https://doi.org/10.1021/acsami.5c13361

28. M. Patra, 2025 EUV Workshop, Boston (June 2025) & in these proceedings

29. Markus Benk, Ryan Miyakawa, Weilun Chao, Bruno La Fontaine, "Mask-side Hyper-NA EUV imaging on the SHARP microscope," J. Micro/Nanopattern. Mats. Metro. 24(1) 014401 (31 March 2025) https://doi.org/10.1117/1.JMM.24.1.014401

30. Inhwan Lee, Joern-Holger Franke, Vicky Philipsen, Kurt Ronse, Stefan De Gendt, Eric Hendrickx, "Hyper NA EUV lithography: an imaging perspective," J. Micro/Nanopattern. Mats. Metro. 22(4) 043202 (14 November 2023) https://doi.org/10.1117/1.JMM.22.4.043202

31. Inhwan Lee, Joern-Holger Franke, Vicky Philipsen, Kurt G. Ronse, Stefan De Gendt, Eric Hendrickx, "Toward practical application of sub-resolution grating for improved process window control in high and hyper NA EUV lithography," J. Micro/Nanopattern. Mats. Metro. 24(4) 043201 (7 October 2025) https://doi.org/10.1117/1.JMM.24.4.043201

32. W. Ethan Maguire, Bruce W. Smith, "Resolution enhancement for high-NA extreme ultraviolet lithography using aperiodic multilayer masks," Proc. SPIE 13424, Optical and EUV Nanolithography XXXVIII, 134240D (22 April 2025); https://doi.org/10.1117/12.3051972