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Report from the Extreme Ultraviolet (EUV) Lithography Working Group Meeting: Current State, Needs, and Path Forward

Version 1.0

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Abstract

This is the report of a hybrid working group meeting held on April 25, 2023, at the National Institute of Standards and Technology (NIST) in Boulder, CO. The working group was focused on extreme ultraviolet lithography (EUVL) research, development, and manufacturing. The meeting allowed for productive discussions on many technical aspects of EUVL. Industry participants gave presentations that helped inform this report's outline of the current state of the science, challenges, needs, and future opportunities for accelerated innovation in EUVL. The report also includes information on some of NIST's efforts that could begin or continue to support the USA semiconductor industry. Cohesively presenting some of NIST's research and capabilities at the working group meeting provided external stakeholders visibility and the opportunity to comment. The meeting was insightful for industry participants learning about NIST's research capabilities. In turn, NIST researchers gained a deeper understanding of the industry's needs to identify where NIST's metrology expertise could assist in EUVL research. The meeting and this report do not, and are not intended to, capture the entire perspective of the EUVL industry but rather serve as a discussion starting point. Future work includes expanding participation, honing NIST research sub-groups to specific needs of EUVL, and executing priority research discussed in the working group meeting or any future meetings. Through engagement with the USA EUVL industry, targeted research collaborations are hoped to be created, accelerating semiconductor manufacturing innovation and generating meaningful value for USA taxpayers.

Keywords

Advanced Manufacturing; Chips; Domestic Manufacturing; Extreme Ultraviolet Lithography (EUVL); Semiconductor; Stakeholder Collaboration.

Organizing Committee

Elizabeth G. Rasmussen, NIST, Chair

Boris Wilthan, NIST

Brian Simonds, NIST

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Acknowledgments

The authors thank all participants of the April 2023 extreme ultraviolet (EUV) lithography working group meeting. A complete list of speakers and attendees is provided in Appendix A. Special thanks are extended to the members of the planning committee listed below. The committee was responsible for all essential groundwork for the event and the contents of this report.

Presentations from invited speakers and panel discussions at the workshop provided the foundation for this report. Without the enthusiastic participation of all workshop attendees, this report would not have been possible. Many thanks are also due to the conference support staff of NIST, especially Andrew Uribe, Wendi Copello, Michelle Slone, Benjamin Jeanette, and Joseph Nastus, who ensured the meeting logistics were handled with excellence and efficiency. Special thanks are also due to our tour sponsors, Justin Shaw, and Brian Simonds, who opened their laboratory doors for attendees to experience a safe and informative tour. Joseph Kline of NIST also provided strong counsel regarding the working group meeting logistics and scope, which was greatly appreciated. Lastly, many thanks to our panel members, panel moderators, and volunteer rapporteurs, who are listed on the title pages of each of the workshop panel sections.

Author Contributions

Elizabeth Rasmussen: Conceptualization, Visualization, Supervision, Project administration, Writing- Original draft preparation, Writing- Reviewing and Editing; **Boris Wilthan**: Writing- Reviewing and Editing; **Brian Simonds**: Writing- Reviewing and Editing.

Executive Summary

One of the main advancements in semiconductor manufacturing is using extreme ultraviolet (EUV) light (13.5 nm wavelength) for lithography. EUV light allows smaller features to be built on a semiconductor, increasing device area density. Developing commercial high-throughput EUV instruments has created the ability to mass-produce advanced microchips incorporating novel transistor designs and chip architectures. This competitive advantage in microchip fabrication has led to stringent export controls of the technology. Specifically, in October 2022, the United States of America (USA) Bureau of Industry and Security (BIS) released a rule, 87 FR 62186, that includes ultraviolet photolithography in the EUV range (b.2).

A working group met in April 2023 at the NIST Boulder, Colorado campus. The meeting provided a space for some key U.S. EUV lithography industry leaders to present top-priority technical problems and views on metrology advancements needed to strengthen the U.S. position in EUV lithography research, development, and manufacturing to relevant NIST staff. Additionally, NIST researchers illustrated their capabilities through research presentations and laboratory tours. The intention for this working group meeting was to (a) provide industry visibility to NIST researchers and laboratory capabilities; (b) welcome industry feedback on useful research directions for NIST to support the U.S. semiconductor industry; (c) avoid parallel programs being submitted to, or funded by, the CHIPS R&D Metrology Program by NIST scientists; (d) ensure NIST researchers are aware of similarities and differences in their research ideas and capabilities; and (e) aid in aligning the unique metrology skillset of NIST with impactful problems facing the U.S. EUV semiconductor industry.

Five technical EUV Lithography (EUVL) topics were covered. Understanding the complexity of each topic and how they support each other is vital to grasping the EUVL ecosystem, thus, they are briefly outlined below. Industry recommendations from these five topics are included. In all five technical topics, the value of experiments currently outweighs theory or simulations. However, theoretical advancements that understand underlying physics is desired to build predictive models. Such work requires solid experimental data supported by accurate and precise metrology. NIST has unique experimental metrology skillsets and theoretical simulation programs for EUVL. NIST efforts should be made to create or use instruments that provide the highest possible accuracy data relevant to the EUVL industry. NIST should contribute to physics modeling by providing expertise in identifying the code base that will produce the most accurate and ideally predictive capabilities for the industry.

<u>EUV Light Source:</u> A droplet generator instrument must dispense molten tin continuously and reliably. The droplet generator is the ‘heartbeat of EUV’ as droplet timing triggers a laser pulse to create EUV light.

> *Industry Recommendation:* To increase performance, create reference-quality thermophysical property measurements of pure tin at extreme conditions (>500 K, >10 MPa) and disseminate data in a Standard Reference Data (SRD) format.

<u>Radiometry for EUV generation:</u> Accurate quantification of the laser light used to energize the molten tin droplets and of the subsequent plasma / 13.5 nm light emission.

Industry Recommendation: Provide a traceability chain for all light (high-power infrared laser and plasma emission) under conditions relevant to EUV lithography.

EUV Plasma Physics and Modeling: Once the laser hits the tin droplet light source, an accurate physical understanding of the light/matter interaction is needed.

Industry Recommendation: Simulation that can achieve predictive capabilities utilizing validation and verification of advanced collisional-radiative and radiation transport codes. Experiments of modeling would ground current models, expanding the groundwork of cohesion across international code bases to have a 'best' model selection grounded in data-driven models.

EUV Photoresists: With the EUV light, the photoresists are critical to the pattern, but understanding/probing material behavior is needed at every length scale to increase yield.

Industry Recommendation: Supply chemical speciation measurements on process variations at every length scale and increasingly in three dimensions for stochastic defects in resists. Create high-throughput metrology to characterize process variation among features.

EUV Collector Mirrors: a multilayer mirror that directs the EUV light to the photoresist template, yet tin debris cause costly inefficiencies in production.

Industry Recommendation: NIST offers position-dependent EUV reflectivity measurements for condenser optics. This data allows end users to assess optic lifetimes and the effectiveness of tin debris mitigation techniques.

Industry has methods to support domestic interests, but NIST scientific and management leaders should understand how to align any new intellectual property accordingly. Established methods for controlled dissemination, like cooperative research and development agreements (CRADAs) as well as disseminations as Standard Reference Data (SRD) and Standard Reference Materials (SRM) should be considered.

The two programmatic findings and subsequent recommendations in the working group meeting are:

1. The internationally competitive landscape of EUVL leads to non-disclosure agreements (NDAs) being required to have deep technical conversations with NIST researchers. A recommendation was to streamline the NDA process between NIST researchers and the industry for a turnaround of two months from the project initiation. Education should be given to NIST staff and management about the NDA process to execute steps correctly.

2. In-person interactions yield productive conversations and actionable next steps. Future stakeholder interactions could transition from working group meetings *to* workshops *to* consortiums, yet this transition leads to increased cost ($10k - $100k+) and planning effort (40 – 200+ hours). To help mitigate cost and effort, future events could occur at commonly attended professional conferences.

Possible future actions by the working group include expanding NIST and industry participation, honing research sub-groups to target specific needs of EUVL, and executing priority research discussed in the working group meeting and any larger future meetings. Through engagement with the USA EUVL industry, it is envisioned that collaborations are fueled, and semiconductor manufacturing innovation is accelerated, thus creating meaningful value for USA taxpayers.

1. Introduction

In 2022 the market size for semiconductors was about $0.6tn, which business analysts expected to double to between $1.0tn and $1.3tn by 2030 [1, 2]. A large area of growth in semiconductor manufacturing can be found in the lithography process. Lithography is a patterning process where a planar design is transferred to the surface of a wafer substrate, creating complex structures like transistors and wire interconnects. This is done by selectively exposing a light-sensitive polymer, or photoresist, to particular wavelengths of light through a complex multi-step process [3]. Recently, advances in lithography have created a competitive advantage in producing the most advanced semiconductors, enabling the most advanced technologies like artificial intelligence (AI), 5G telecommunications, and supercomputing. Advanced semiconductors consequently affect national security and economic prosperity [4].

Today's most advanced semiconductor lithography process uses an EUV light source, specifically light at 13.5 nm. EUV light allows for smaller features to be built into a semiconductor. EUVL systems currently cost a reported $150 million and were first deployed in 2019 by ASML, which maintains a 100% market share [5]. To date, ASML has shipped three different EUVL system models, namely the Twinscan NXE:3400 B/C and NXE:3600D, with the total number of NXE systems shipped growing from 31 in the first quarter of 2019 to 181 in the last quarter of 2022.[1]

The organization of this report is as follows. The remaining parts of the introduction include a technical background on EUVL (Sec. 1.1), a background on the international and domestic state of EUVL (Sec. 1.2), and an overview of NIST and CHIPS R&D metrology program (Sec. 1.3). Section 2 contains the technical state and needs of EUVL as discussed in the working group meeting. Section 3 concludes the report by outlining the working group meeting's findings and recommendations for paths forward.

1.1. Technical Background on EUV Lithography

EUVL is a key step in the fabrication of next-generation semiconductor chips. EUV light is produced by a high-temperature plasma generated from high-purity tin. Solid tin is melted inside a droplet generator instrument that continuously produces over 3 million 27 µm liquid droplets per minute in a vacuum chamber. A pulsed 25 kW average power carbon dioxide (CO_2) laser irradiates a tin droplet with two successive pulses to shape and then ionize the droplet, respectively. Initially, thousands of watts of EUV light are generated, yet only a small fraction makes it to the photolithography mask due to absorption and scattering losses along the optical path. Output power and beam quality of the 13.5 nm light are inferred from indirect scintillator-camera measurements. A system of multilayer collector mirrors directs the light to a light-sensitive

[1] Certain equipment, instruments, software, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement of any product or service by NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

polymer, or photoresist, which transfers a pattern onto a wafer. The mirrors are protected from tin debris through a constant flow of H_2 gas. An automated wafer stage positions the wafer at resolutions of ≤0.25 nm after each exposure, with a cyclical check-adjust process occurring 20,000 times per second. Overall, the process requires precise coordination between many disparate engineering systems. Fig. 1 shows a photograph of an ASML EUVL assembly.

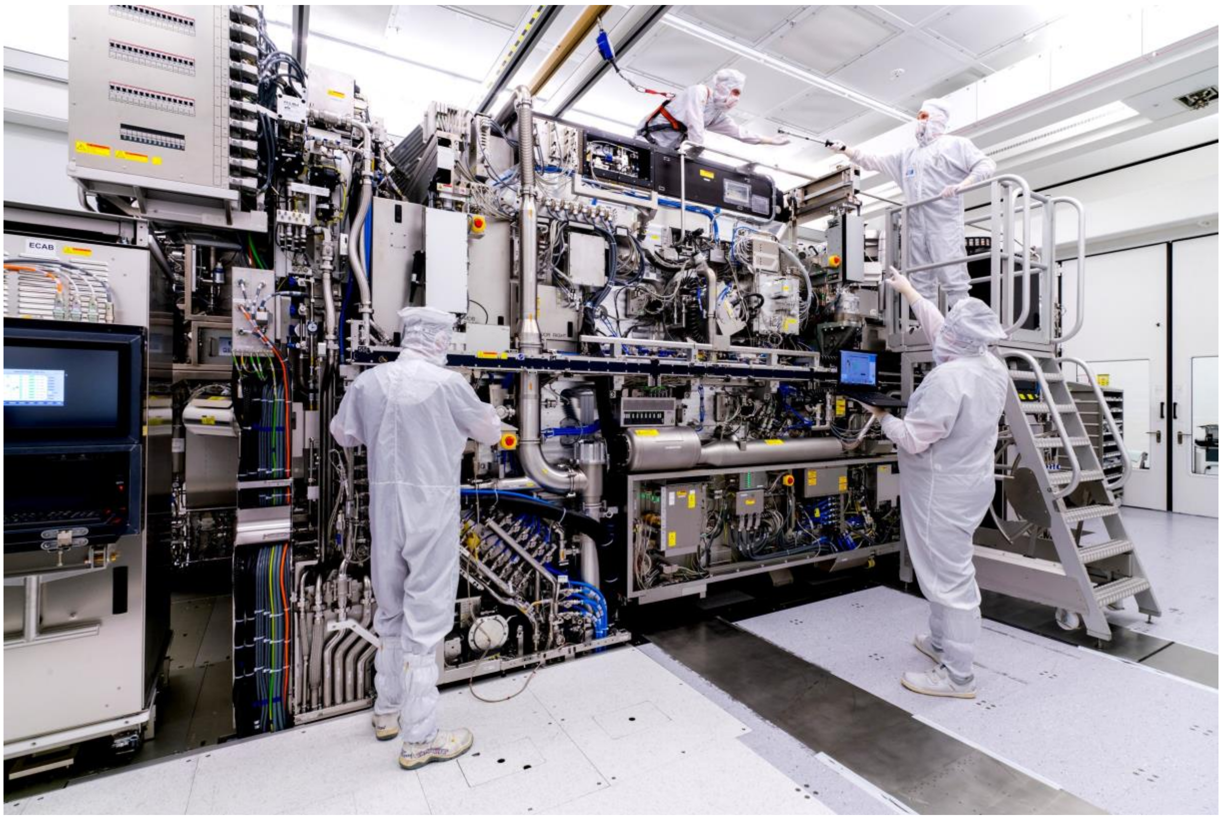

Fig. 1. Photograph of an ASML EUVL assembly. Image Source: [5], Photograph: ASML

1.2. Current and Future State of EUV Lithography

Growth in advanced semiconductor manufacturing is occurring from new EUV fabrication facilities in the USA as well as European and Asian countries. As mentioned earlier, the only company that currently manufactures EUVL scanner assemblies is ASML based in the Netherlands. ASML sells the EUV scanner assemblies to companies like Intel, the Taiwan-based Taiwan Semiconductor Manufacturing Company (TSMC), and the South Korea-based Samsung. These companies then implement the EUV scanners in their semiconductor fabrication facilities. The EUVL systems are not created solely in the Netherlands but consist of many modules developed across the globe that are then shipped to ASML headquarters in the Netherlands for final assembly and testing before being delivered to customers. The reader is directed to a recent report by Khan *et al.* of the Center for Security and Emerging Technology for further details about the supply chain implications of a single supplier within the microelectronics manufacturing ecosystem [6].

From the United States perspective, ASML's research, development, and manufacturing of the EUV source is stationed in San Diego, CA. The source component of the EUVL scanner assembly can be seen in Fig. 2. It should be noted that the source components include the source vessel, positioned in the EUVL scanner assembly, plus many components below the fabrication floor including laser metrology, beam-transport system, and the drive laser and its ancillaries. The source work being stationed in San Diego is a result of ASML acquiring Cymer in 2012 to advance the development of the EUV source technology [7]. Furthermore, given the advantage of EUVL for semiconductor manufacturing, export controls have recently guarded the technology. Specifically, in October 2022, the USA Bureau of Industry and Security (BIS) released a rule, 87 FR 62186, that includes extreme ultraviolet photolithography (b.2) [8].

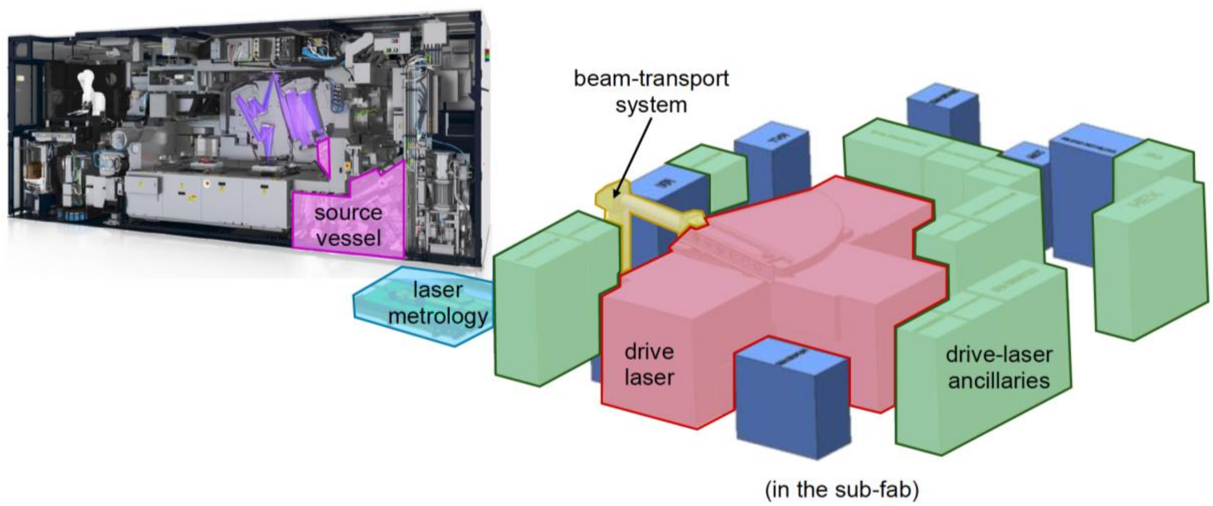

Fig. 2. Graphic of ASML's EUV Lithography source components. Image Credit: ASML

ASML has stated that future development of EUV lithography includes increasing the numerical aperture (NA) from 0.33 to 0.55 ('High-NA'). The High-NA can be used to reduce the number of multi-patterning steps required today for 0.33 NA and leads to resolving finer geometry sizes. This is aligned with the openly published 2022 IEEE International Roadmap for Devices and Systems (IRDS) roadmap and necessary to continue to scale transistors to 0.5 nm by 2037. The goal of the new NA platforms is to increase the speed of wafer and reticle states to enable geometric chip scaling. The High-NA systems are expected to be shipped to customers in 2023, with full platforms of the process for high-volume manufacturing expected to be operational by 2025. In early 2023 ASML announced that they had set two new EUV power records of a one-hour run of 600 W EUV emission meeting the High-NA EXE:5200 dose stability specifications and 700 W in open loop operation. The 600 W demonstration is an increase over the 250 W delivered five years before enabling EUV high-volume manufacturing [9]. Details on the 600 W power demonstration regarding the droplet generator and laser power are included in Sec. 2.1 and Sec. 2.2. Additional details on High-NA are outside the scope of this report. Nevertheless, the reader is directed to a 2022 peer-reviewed paper by Levinson for additional thoughts on the current status and outlook for High-NA EUVL [10].

Understanding the international and domestic landscape of EUVL aids in understanding research and development collaboration opportunities. Furthermore, it underlines the competitive landscape of the technology space and the necessity for scientific leadership. Finally, given that CHIPS Act funding is to increase the resiliency of USA semiconductor manufacturing, one must be aware of the importance of assisting the production of this key manufacturing process via best-in-class metrology practices.

1.3. Overview of NIST and CHIPS R&D Metrology Program

Dr. Marla Dowell, Ph.D., M.B.A., the director of the CHIPS R&D Metrology Program and NIST Boulder Laboratory, provided a welcome keynote address at the working group meeting. The keynote address began by reminding the attendees of NIST's mission:

> *To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.*

It highlighted NIST's core competencies of (1) measurement science, (2) rigorous traceability, and (3) the development and use of standards. Dr. Dowell provided additional context on the CHIPS R&D Metrology programmatic details, organizational relationships, and national research facilities at NIST. Dr. Dowell emphasized the need for joint research between industry and NIST to collaboratively solve pressing microelectronics challenges critical to CHIPS. The audience was reminded that NIST is a non-regulatory laboratory. As such, NIST has been a trusted partner of proprietary information; is a neutral, objective broker; and promotes the development of critical technologies by disseminating high-quality measurements, data, and research supporting U.S. innovation and industrial competitiveness. Specifically, in the Boulder, CO campus NIST has about 900 staff and over 500,000 square feet of laboratory space that covers six areas, including (1) Advanced Communications Technologies, (2) Quantum Science & Engineering, (3) Time & Frequency Metrology (4) Advanced Materials Characterization (5) Precision Imaging (6) Lasers and Optoelectronics. Dr. Dowell then emphasized that NIST has a long history and broad portfolio of target investments in microelectronics spanning many areas.

Dr. Dowell later transitioned to presenting on the CHIPS for America Act. An overview of the strategy for the CHIPS for America Fund was given, including how it will support three distinct initiatives: (1) Large-scale investments in leading-edge manufacturing. (2) New manufacturing capacity for mature and current-generation chips, new and specialty technologies, and for semiconductor industry suppliers. (3) Initiatives to strengthen U.S. leadership in R&D. Differentiation was given between the $39 billion incentives for manufacturing and the $11 billion for R&D, with a highlight towards the R&D funds and the NIST measurement science portion of the appropriation. Dr. Dowell discussed how, through seven identified strategic opportunities for U.S. semiconductor manufacturing, extensive feedback from stakeholders across industry, academia, and government would be sought in many formats, including events such as this working group meeting for EUVL [11]. An example of metrology for materials was provided from the Communications Technology Laboratory (CTL), where she served as the operating unit director before becoming the CHIPS R&D Metrology Program director – specifically standard reference materials (SRMs) for 5G materials. As an example of the ability of metrology to enhance the security and provenance of microelectronic-based components and products, the NIST SP1278 document, which she co-authored, was highlighted [12].

To conclude the keynote presentation, Dr. Dowell informed the attendees of the NIST publication from August 2022 that presented CHIPS-related metrology opportunities [13]. Additionally, a document released that morning, April 25, 2023, by her department outlined a vision and strategy for the National Semiconductor Technology Center, describing how future interaction between industry and NIST could occur [14].

Dr. Stephanie Hooker, Ph.D., acting director of NIST's Material Measurement Laboratory (MML), provided a keynote address at the working group meeting to welcome attendees prior to the afternoon sessions. Dr. Hooker restated the NIST mission and emphasized that NIST's greatest strength is its reputation of world-class leading engineers and scientists. In addition to sharing NIST's size and capabilities, a focus was placed on the measurement services that NIST offers. The measurement services include over 1,100 Standard Reference Materials (SRMs), about 100 Standard Reference Data (SRD) products, five quality assurance programs, and numerous data tools and registries. Emphasis was also placed on documentary standards and how over 400 NIST technical staff were involved in over 100 standard committees and held leadership positions in many international standards bodies. Being engaged in standards thus enhances U.S. competitiveness on a global scale. Her presentation highlighted the critical technology areas that NIST is involved in and is expanding upon, including artificial intelligence (AI), quantum science, advanced communications, advanced manufacturing, and the bioeconomy. Dr. Hooker concluded by presenting some of the established engagement areas and ways to collaborate with NIST, including working group meetings like the one this report focuses on, consortia, CRADAs, and material transfer agreements (MTAs).

These two keynotes showed cohesion and engagement between the working group members and NIST leadership, which thus energized discussions throughout the day's activities.

2. Technical Aspects of EUVL

The technical aspects of EUVL that were presented and discussed at the working group meeting are now detailed. Three sections are dedicated to discussing the EUV source module (Sec. 2.1 through 2.3). Then, the current state and needs of characterizing components that interact with the EUV light are discussed (Sec. 2.4). Both components that interact with EUV light in Sec. 2.4 have technical research ties to Sec. 2.1 through 2.3. Finally, how EUV light has been used as a metrology tool to analyze components in the semiconductor manufacturing process is presented (Sec. 2.5). The metrology aspects of EUV light as a tool has direct relationships to radiometry discussed in Sec. 2.2. The sections are technically deep and demonstrate the interrelationship of the metrology, light generation, and semiconductor materials operating within the EUVL ecosystem. Technical details discussed here have already been publicly released. Nevertheless, combining industry and NIST research technical expertise and status into one report is useful for understanding the technology landscape. Review references have been included to supplement the technical details provided in this report.

2.1. Droplet Generator: Thermophysical Properties and Modeling at Extreme Conditions

The droplet generator is a vital component in the EUVL scanner assembly (Fig. 3). The droplet generator controls the size, velocity, and repetition rate of material that enters the EUV source chamber to be ionized by the CO_2 laser creating the 13.5 nm EUV light. Thus, droplets must be reliably delivered for EUV light to be generated as malfunctions affect all downstream components, halting operation. Droplets have a typical diameter of 27 μm and travel at 80 m/s with a 50 kHz repetition rate. The droplet generator triggers the emission of the CO_2 laser pulse leading it to be referenced as the ‘heartbeat’ of the entire EUV scanner assembly.

Tin is the working fluid for droplet generators in EUVL applications because of the specific 13.5 nm wavelength of light it generates when ionized into a plasma. Over recent decades, researchers looked at the possibility of materials other than tin, like xenon and lithium [15]. Factors like safety, cost, and performance have proven tin to be the superior material for laser-produced plasma in EUVL manufacturing applications. There is no public roadmap for a material other than tin for the EUV source in semiconductor manufacturing, so investment in understanding this material at a fundamental science level will be impactful in the near- and long-term future. The industry's alignment on a single material source, tin, makes it ideal to invest additional effort to understand the fundamental material properties necessary to generate the complex laser-matter interaction used to create EUV light.

The operating principle of the droplet generator is that solid high-purity tin (>99.999 wt.%) is loaded into a vessel and heated above its melting point (~ 232°C). Then pressure is applied to one side of the liquid in the vessel by a high-purity gas, usually nitrogen, causing molten tin to flow through a filter to a nozzle at the other side [16]. A jet of tin droplets is usually modulated by a piezoelectric (PZT) crystal that creates mechanical vibrations. A schematic of a first-generation droplet generator with a photograph of it can be seen in Fig. 3. The droplet position stability σ is about 1 μm.

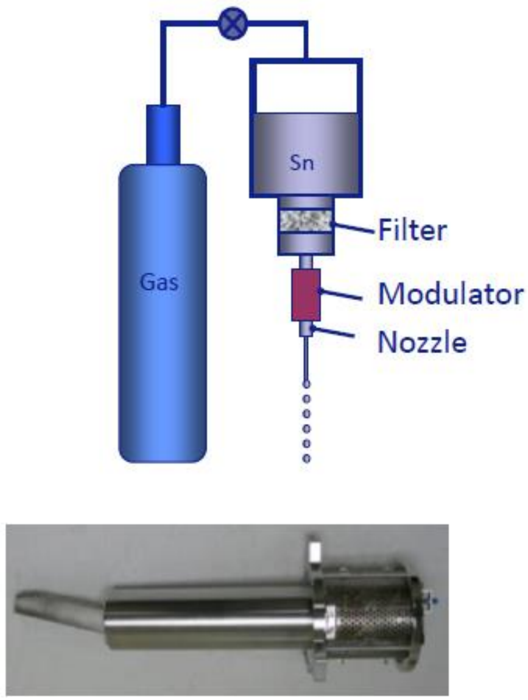

Fig. 3. Schematic (top) and photograph (bottom) of a tin droplet generator. Image Credit: ASML

A new advancement in the droplet generator was made in 2021 with in-line refill capabilities, Fig. 4, that reduced system downtime without interrupting the downstream EUV scanner performance [17]. Over 3000 hours of continuous operation has been achieved using this new droplet generator design.

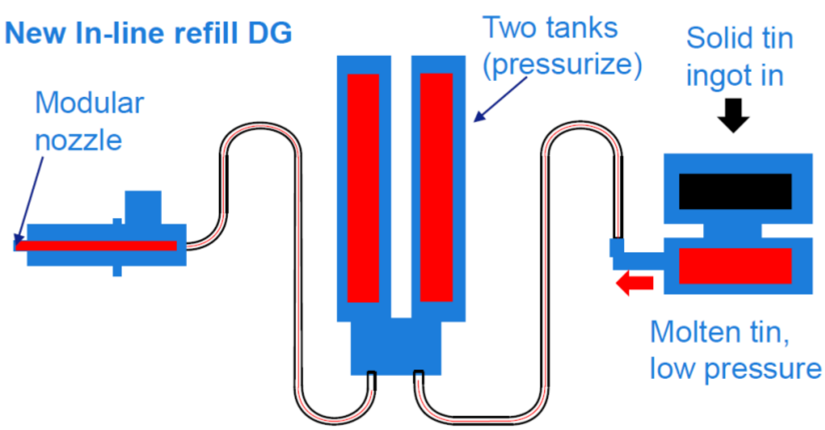

Fig. 4. Schematic of the tin droplet generator with inline refill. Image Credit: Purvis *et al.* [17]

Increasing productivity to have higher EUV power requires increased drive laser power (covered in Sec. 2.2.) and more droplets per second. To increase the droplet frequency, the droplet generator pressure needs to increase, which in turn creates a larger droplet spacing. This is shown conceptually in Fig. 5.

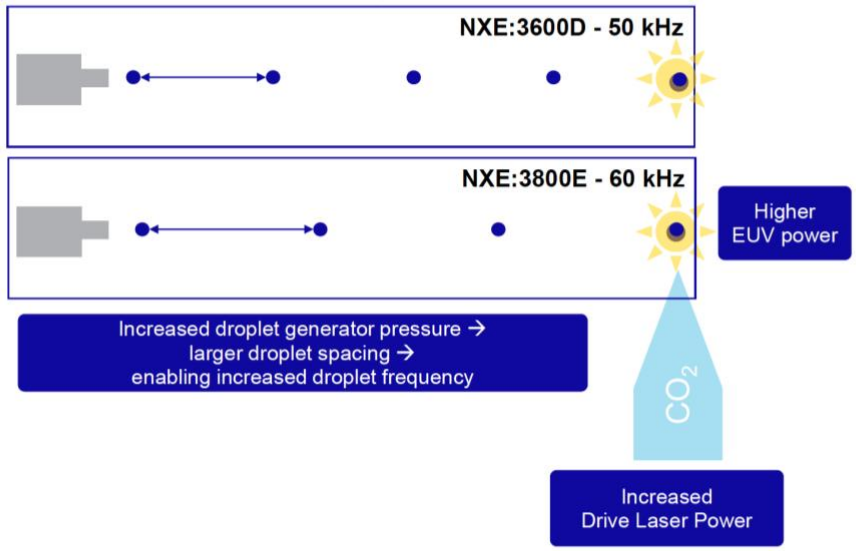

Fig. 5. Schematic in the spatial domain of the droplet generator with different operating pressures to enable higher EUV power. Image Credit: ASML [18]

There is currently a lack of reliable material properties for molten metals at pressures above atmospheric pressure. This lack of standard data hinders efforts to create numerical simulations of the droplet generator. The current practice described by scientists and engineers involves sourcing the nearest material properties from published literature and extrapolating rough estimates. They then rely on empirical observations of the entire system at operating conditions to tune the relationship between material properties and operating parameters. An industry speaker gave a case example of how the printhead design requires the balance of making sure the working fluid (molten metal) was at a high enough temperature to be in the liquid phase, but also not too high to melt the piezoelectric components.

Current NIST metrology resources for metal material properties were presented, with emphasis on the NIST Alloy Database, which is a curated database containing experimental thermophysical properties of metals, including tin [19, 20]. Currently, the entire database is free and open to the public due to funding by the Materials Genome Initiative (MGI) and overseen by the Thermodynamic Research Center (TRC) [21, 22]. To continue development, transitioning the database to SRD is possible so that the cost of upkeep is accounted for in accordance with the US Standard Reference Data Act Update law passed in 2017 [23, 24]. The ability to provide the USA industry with unbiased and expertly validated material property data could provide productive design insights and innovation in operating the droplet generator. The advantages of SRD for material properties have been noted internationally, as evidenced by a recent publication from the South Korea Metrology Institute [25].

A limiting factor to the usefulness of NIST metrology capabilities is a gap in experimental data for molten tin at the high pressures applicable to EUVL's droplet generator. Material properties of the working fluid in a droplet generator dictate the phenomenon called Rayleigh breakup, which causes the droplets to form and undergo coalescence. This phenomenon has been well-studied over the past 40 years [26-28]. Research by the Swiss Federal Institute of Technology Zurich in 2011 by Rollinger *et al.* demonstrated the relationship between pressure up to 4 MPa and frequency up to 100 kHz for molten tin droplet's diameter and velocity [29]. A publication in 2023 by Chinese researchers shows active pursuits in the research space [30].

Given the missing reference data for molten tin, new instruments that can measure reference quality data to populate a database like the NIST Alloy Database would be valuable. The speed of sound (SoS) is a particularly useful material property because it can be combined with density and isobaric heat capacity data at a *single* (T, p) point allowing one to derive the additional thermophysical properties of density, isobaric expansivity, and isobaric heat capacity at *any* temperature, T, and pressure, p. The value of the SoS measurement has been shown by researchers at NIST for refrigerant materials [31]. Accurate SoS measurements are crucial to reaching the ultimate goal of modeling a material's thermodynamic properties by use of an equation of state (EoS) [32]. The use of different EoS's on the accuracy of simulations has been shown to have a dramatic effect on accuracy for even the simplest geometries [33]. An instrument is currently in development at NIST to measure the SoS at elevated pressures and temperatures. The SoS instrument was part of Dr. Elizabeth Rasmussen's National Research Council (NRC) postdoctoral fellowship for additive manufacturing of metals. A US patent on the instrument design and operation was submitted in October 2022 [34]. The new metal SoS instrument is an extension of an existing instrument at NIST that operates at less extreme temperatures and pressures [31]. The new instrument is currently under development, and additional dedicated resources are necessary to make tin measurements.

An additional need was expressed for transport property data (surface tension, viscosity, etc.) of molten tin at extreme conditions. Fulfilling this need would require a new custom metrology instrument and associated resources. Both the SoS and transport property instruments would have world-class metrology capabilities and thus require specialized skills to execute the design, fabrication, and operation.

Once data are collected, it is useful to correlate it in an EoS. An example of such dissemination is transport correlations or thermodynamic EoS. There is currently a reference correlation for the transport properties of tin but no reference EoS [35]. The correlation for tin transport properties differs from experimental data by 5-10% and is only valid at atmospheric pressure. This leads to an opportunity for advanced metrology. NIST has expertise in creating reference correlations, EoS, and SRD for refrigerant and natural gas materials dating back to the 1990's through the REFPROP (REFerence fluid PROPerties) program. Thus, measurements could be made similarly for metals, specifically for tin, and an EoS developed into SRD to empower high-fidelity simulations and enable data driven EUVL development. Such development could include increased EUV emission and digital twin creation, which reference material properties, reference correlations, and EoS would enable. Dissemination of SRD or models to the U.S. industry could happen in a controlled fashion via the established SRD program at NIST, Fig. 6.

Currently, no commercial software system can provide accurate or predictive simulation guidance concerning liquid phase metals above atmospheric pressure. This metrology endeavor was eagerly encouraged by industry members of the working group from the perspective of both a user of the data and conduit of the data in simulations.

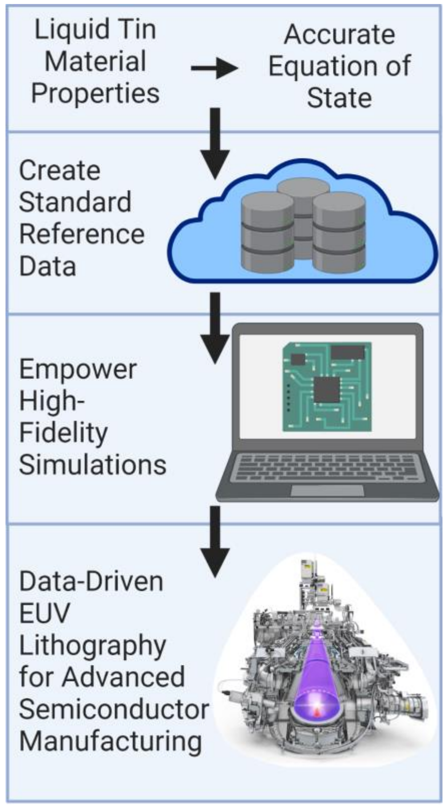

Fig. 6. Flow diagram of how liquid tin material properties could assist in droplet generator operation for data driven EUV lithography.

In addition to a lack of thermodynamic and transport properties at extreme temperatures and pressures, there is limited structural and piezoelectric data on components. This restricts droplet generator design by limiting the ability to predict possible material incompatibility. A discussion on how new, high-temperature (> 300°C) piezoelectric materials were mentioned as an advantage to the current setup. A member mentioned and shared a reference to a recent publication by Tittmann *et al.* that such materials existed, but they were less available and more expensive [36]. Thus, a tradeoff would have to be made.

Metal droplet generators exist beyond pure tin and have been used for decades for applications like soldering and creating powder for metal additive manufacturing, including for alloys of lead, tin, indium, copper, silver, and gold. Given the maturity of the application area, it was surprising to note that there is a large knowledge gap in basic underlying material properties. Although droplet generator use beyond EUVL was out of the scope of the working group, it was useful to be aware that development in this area could also affect other critical technology areas.

In conclusion, optimizing the droplet generator instrument within the EUVL scanner assembly was emphasized. The need for continuous, reliable, and precise operation of the droplet generator was made clear, as well as for advancements in the design that enables improved EUV chip production. Metrology advancements with respect to measuring basic thermodynamic and transport properties of molten tin at elevated pressures could enable reference correlations to be created for material properties and disseminated in the form of SRD. Integrating SRD into simulation software could allow for digital twin simulations of the droplet generator. Being able to simulate the environment of the droplet generator could thus aid in the operation of current devices and innovation for future designs that enable High-NA EUV scanner systems.

2.2. Radiometry for EUV generation

Industrial EUVL tools involve primarily two types of light: pulsed, high-power infrared (IR) laser light for ionizing molten tin (Sn), and the 13.5 nm light generated for lithography. The former is provided by a purpose-built CO_2 laser ($\lambda = 10.6$ µm) emitting around 30 kW (average power) at a 50 kHz repetition rate. The process of tin ionization involves two IR laser pulses in rapid succession: a pre-pulse to flatten the droplet from a sphere into a disc and a second, higher-energy main pulse, for ionization [37, 38]. The output of the IR laser is critical for developing future lithography tools as "EUV power scaling requires higher CO_2 laser power…. [37]" The maximum output power of the incoherent 13.5 nm EUV light is about 250 W in current commercial lithography tools with 600 W demonstrated in the laboratory [18]. The two-pulse system is shown in diagram format in Fig. 7.

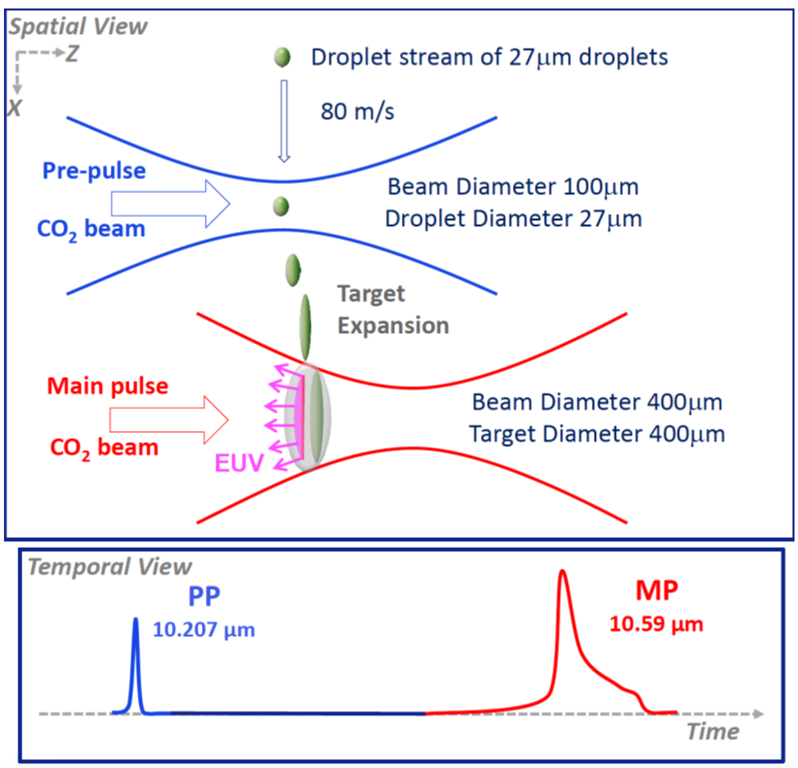

Fig. 7. Diagram showing (top) spatial view and (bottom) temporal view of the two-pulse system to produce EUV light in the semiconductor manufacturing process. Image Source: ASML

NIST currently supports IR calibrations, but not at the power and pulse conditions necessary for commercial EUVL [39]. And although NIST currently offers calibrations to the microfabrication industry targeted for lithography, it is only at 193 nm and 248 nm wavelengths [40-43]. Calibrations in the EUV wavelength regime are possible, but only at significantly lower powers (milliwatts) than EUVL tools produce [44]. At these reduced powers, NIST offers radiation-hardened silicon photodiodes and aluminum oxide photoemissive detectors, or suitable customer-supplied detectors that can be calibrated as a transfer standard. Other optical characterizations are performed in the EUV, including filter transmission and spatial uniformity testing. A metrology research opportunity would be to extend NIST calibration capabilities to cover the input IR laser light, the EUV scintillator used to infer power midstream, and the direct final output EUV light, all under conditions relevant to industrial EUVL. This would have immediate impacts on semiconductor manufacturing process development by providing traceable metrology for key process parameters. In addition, the long-term impact will come from future EUV instrumentation development by providing high-fidelity data for validating simulations of EUV generation.

Absolute radiometry is not only important for lithography process development and instrument acceptance testing but also for accurate quantification of the EUV light generation process. Predictive simulations of this process have lagged the development of the EUV tool itself. Advancing model accuracy requires accurate experimental data of both model inputs and outputs. Developing new radiometric metrology tools specific to the IR laser and 13.5 nm light under conditions relevant to industrial EUV light generation will provide such data.

Developing these detectors cannot be done without industry cooperation, as the industrial lithography tools discussed here are the only ones capable of generating the amount of light these detectors will be designed to measure. Given the amount of intellectual property associated with these tools, it will be important for representatives from government and industry to cooperate. Initial discussions at the working group meeting revealed that industry is reluctant to discuss pertinent details without the protection of a non-disclosure agreement. As this can sometimes be problematic for federal employees, a mutually agreeable solution should be sought for timely and meaningful interactions.

2.3. Plasma Physics and Modeling: Light-Matter Interaction

EUVL makes use of 13.5 nm photons to produce integrated circuits. The primary source of such light is a very hot plasma of tin produced with powerful lasers. The laser parameters are adjusted to generate tin ions that mostly emit near 13.5 nm (examples given: Sn^{10+}-Sn^{15+}). While most plasma characteristics were explored in numerous experiments, reliable and validated theoretical support is paramount to developing better tin plasma sources. The discussion of plasma physics was covered by several presentations throughout the working group meeting and has been combined into one area of the report. This section focuses on discussions about plasma physics, the current technical metrology state, and the needs of the USA industry and NIST researchers to advance the field.

Advanced calculations of light emission from the laser-produced plasmas of tin usually are carried out with large-scale collisional-radiative (CR) codes that attempt to account for the most important physical process responsible for the photon radiation [45]. Those include electron-impact excitation, deexcitation and ionization, radiative, dielectronic and three-body recombination, and autoionization, to name a few. Also, radiation transport and opacity may become necessary, as well as radiative-hydrodynamic modeling.

Plasma modeling is also limited because of limited information regarding the fundamental physical mechanisms underpinning the matter interactions [46]. This can cause plasma engineering efforts to be incremental instead of transformative in support of higher-volume manufacturing. In the past, industry-government laboratory partnerships have sought to understand and thus control the plasma process and have reported their successes [47]. Simulation experts from industry also noted how the complex simulation covers multiple physics domains across varied time scales.

Open questions exist on the utility of plasma modeling for guiding engineering to increase EUV light generation and efficiency. For example, modeling out-of-band photons and the emission of ions and electrons could provide predictive insights that would greatly benefit efficiencies in chip production. Another area of interest is photon, electron, and chemical interaction for EUV photoresists, ongoing research interest in the EUVL industry [48]. Thus, modeling plasma physics is applicable to EUV optical components as well. EUV optics and materials are covered in the following section (Sec. 2.4).

In the last three years, the EUVL modeling community started a long-term validation and verification program of CR codes by organizing EUVL code comparison workshops [49]. This approach is modeled after a series of non-local thermodynamic equilibrium (NLTE) Code Comparison Workshops organized by the NIST Atomic Spectroscopy Group for more than 25 years [50]. As a result, NIST's Atomic Spectroscopy Group (ASG) was asked to develop a new EUVL database and modern comparison tools for intelligent comparisons of CR codes for EUVL [51, 52]. To date, the described work has been successfully performed without direct financial support, and the participants of the last two EUVL workshops used the database and user interface to compare their software packages. Nonetheless, future workshops aim to analyze new physical parameters requiring extensive modifications to the database and the user interface. Therefore, stable funding that indicates long-term, multi-year commitments necessary to support the advancement of this research area is needed.

One future direction NIST researchers reported on was research into even shorter wavelength schemes primarily based on the availability of multi-layered mirrors. This would generate shorter wavelength photons than can be produced from elements heavier than tin in higher ionization states (the so-called "beyond EUV"). Unfortunately, the broader research community's knowledge of spectra from 20+ times ionized high-Z elements is inadequate. The NIST ASG has full experimental and theoretical capabilities to provide the EUVL community with the most accurate spectroscopic data for future plasma sources. To this end, the NIST Electron Beam Ion Trap (EBIT) can not only generate ions with charges as high as 70+ but also record the most accurate and detailed spectra in the EUV and soft X-ray regimes due to the availability of precision spectrometers in this spectral range. The NIST ASG team also performs high-accuracy large-scale spectra calculations with the most advanced atomic methods and codes. The proven competence should satisfy the EUVL's need for accurate data for future plasma sources. It should be noted that when industry representatives were prompted about future sources for EUV, they stated that there are no public plans to use source material other than tin in the near future.

In conclusion, industry stakeholders desire modeling tin plasma, and there is ongoing work at NIST that could support increased efforts but would require investments. Furthermore, the integration of any code into commercial software for design engineers and scientists could be valuable to optimize EUV chip production capabilities. Discussions were technical at the working group meeting, but how any such code would be integrated with a commercial partner to ensure the USA company's benefit should be considered. Finally, modeling plasmas and interactions can aid in decreasing the negative impacts of debris on EUVL components, which will be discussed in Sec. 2.4.2.

2.4. Characterization of Components Interacting with EUV

This section covers two components of EUVL scanner assemblies that interact with EUV light: (1) photoresists and (2) collector mirrors. Industry participants of the working group presented an overarching theme of high-volume manufacturing (HVM) needs. Specifically, HVM interest was focused on increasing the production *and* yield of chips made using EUVL. Some possible metrology solutions that NIST currently has are covered in Sec. 2.5.

2.4.1. Photoresists: Polymer characterization

Photoresist processing is vital to the semiconductor industry. Lithographically fabricated, nanoscale patterns are required for all device elements and related structures — from channels in field-effect transistors (FETs) to electrical interconnects between devices. Rent’s rule states that the number of terminals or interconnects increases with the number of logic blocks or gates [53]. This relates to the cell level that when the standard cell shrinks, connections to the cell need to shrink as well. This concept is demonstrated in Fig. 8.

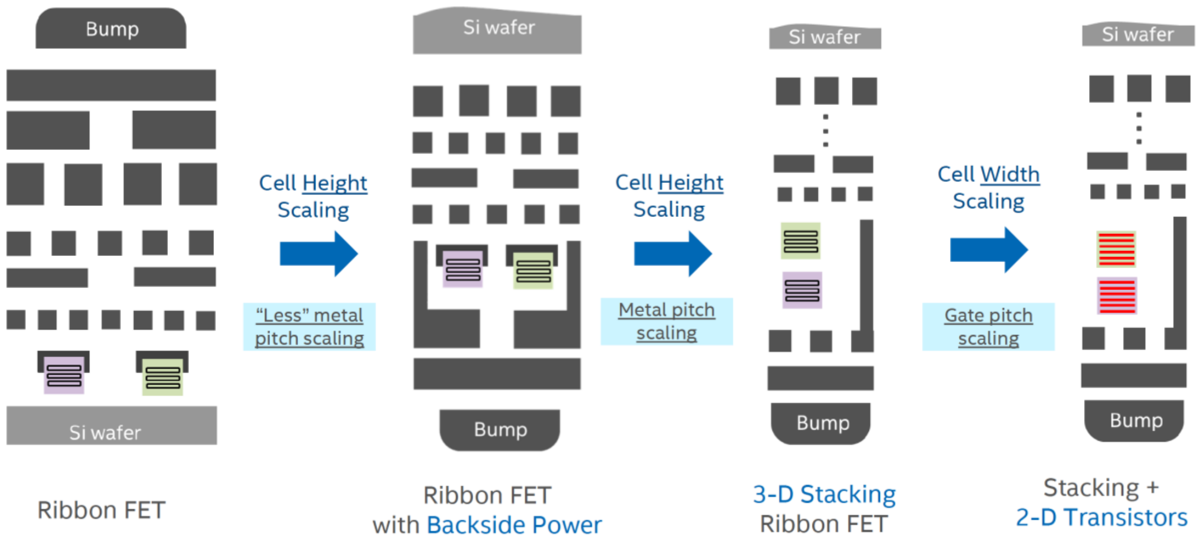

Fig. 8. Example of cell size scaling trends for a ribbon FET where cell width and cell height scaling are needed. Image Credit: Intel, Gstrein *et al.* [54]

Industry participants emphasized how aggressive pitch scaling is required to take advantage of new cell architectures and novel device materials. There was also discussion on how achieving HVM of novel cell architectures and materials is difficult, with yield being a major concern. For example, given 10^{10} contacts per die and a die yield, $Y_d = \frac{good\ die}{total\ die}$, of at least 99%. In context, a 3rd Generation Intel Core processor — quad core, contains 1.48 billion transistors. At 99% yield, 1.48 million transistors would be defective - the target is 99.99996% yield or 6 Sigma (6σ). Yield must be very good – and yield is all about process control and defects. If yield is sufficient, the cost of manufacturing EUV chips is determined by productivity (throughput). In other words, better pitch resolution is necessary but not sufficient for HVM.

A primary process variation that can impact yield is edge placement error (EPE). This occurs when edges and sidewalls of photoresist line patterns display unintended nanoscale irregularities [55, 56]. These irregularities are stochastic and are known colloquially as line-edge roughness (LER) artifacts [57]. LER artifacts could seriously impact dimension control as device sizes continue to shrink and the magnitude of stochastic LER fluctuations begin to compete with line-pattern tolerances. Control of LER is critical for both advancing device performance and manufacturing yield. LER can arise from numerous factors in the processing stream, including errors in lithography and etching steps and nanoscale variations in photoresist chemistry. Therefore, the EUVL industry needs a better understanding of the causes of LER as well as new tools to mitigate these problems.

One of the strategies to decrease errors in the line/space resist rectification is by directed self-assembly (DSA), as it heals defects smaller than the pitch [58]. An example of how EUV + DSA works is shown in Fig. 9. A case study was presented by an industry member at the working group meeting for the synergistic combination of EUV, DSA, and self-aligned double patterning (SADP) for metal pitch at 18 nm and 21 nm.

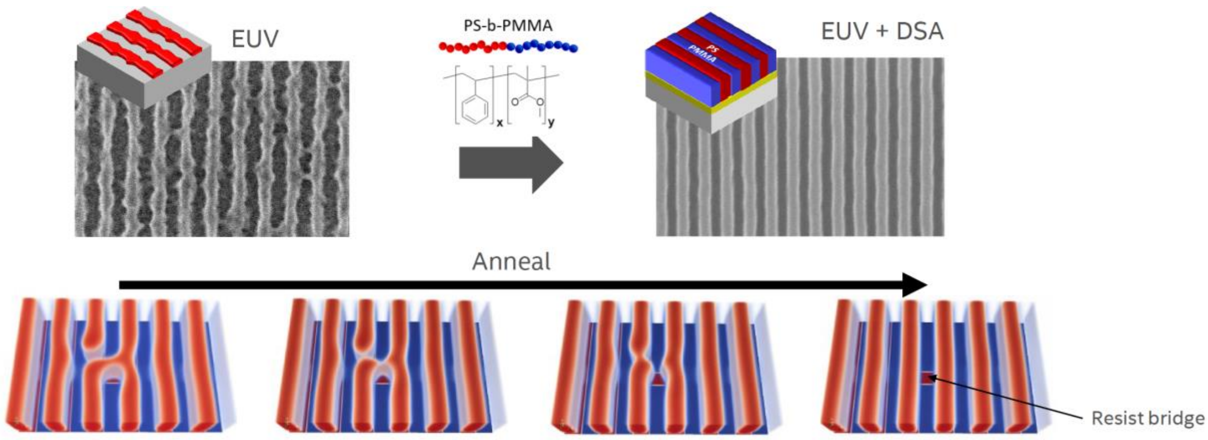

Fig. 9. Example of how using directed self-assembly (DSA) in addition to EUV photoresists improves systematic and random variability. Image Source: Intel

To summarize, the key points surrounding EUV photoresists are that cell size scaling requires novel process architecture, novel device materials, and aggressive interconnect pitch scaling down 12 nm pitch. If the die yield is sufficiently high, EUVL semiconductor chip costs are primarily limited by productivity (throughput). Yield is mostly determined by random process variations that lead to edge placement errors. Metal oxide resist platforms show impressive resolution and defect performance at a tight pitch, and DSA fundamentally improves systematic and random variations in photoresists.

Finally, industry participants emphasized that every current process variation needs to be experimentally probed, and NIST metrology capabilities and expertise plays a key role in these activities. Specifically, four main sub-sections of the experimental probing for process variation:

(1) There is a need to assess process variations among hundreds of billions of features, so high throughput methods that are lab size are needed, potentially like a high-harmonic generation (HHG) device, which will be discussed in Sec. 2.5.1

(2) Chemical speciation of stochastic defects in the resist is an indispensable tool – analysis which can be done in synchrotron source, which will be discussed in Sec. 2.5.2

(3) Process variations need to be probed at every length scale and increasingly in 3-D. Note that this can be done using techniques of atom probe tomography (APT), which will be discussed in Sec. 2.5.3.

(4) At these small length scales, surfaces and interfaces dominate so that there is no such thing as a sharp interface

When asked about the outlook and what industry's message to the research community would be, a list of needs was provided. For photoresists: (a) Novel resists with higher quantum yield and higher contrast (b) Resist/underlayer characterization and origin of defect formation (c) Chemical speciation of stochastic defects in MOx resists (d) resist scum mitigation strategies for organic resists (e) dry development techniques for organic resists. This need is especially relevant as EUVL manufacturing transitions from low-NA to High-NA and beyond, Fig. 10.

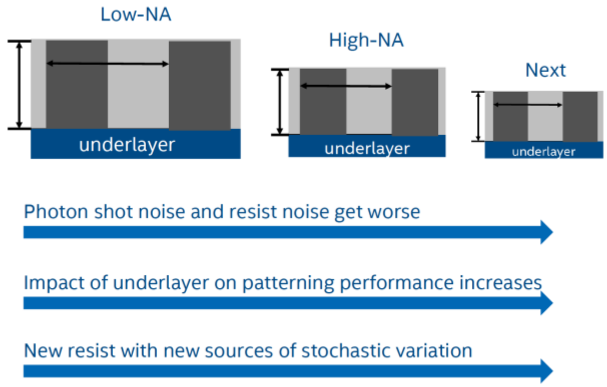

Fig. 10. Diagram showing how new photoresists are needed as the numerical aperture (NA) in EUVL manufacturing transitions from Low-NA to High-NA, and beyond. Image Credit: Intel

For rectification, the industry needs are (a) pitch-independent rectification of roughness and defects to preserve the target layout as shown in Fig. 11, (b) new DSA molecules with high-chi materials with highly selective dry etch and selective infiltration, (c) 3-ton A-B-C block copolymers, and (d) functional block copolymers and brushes (photo patternable, cross-linkable, etc.).

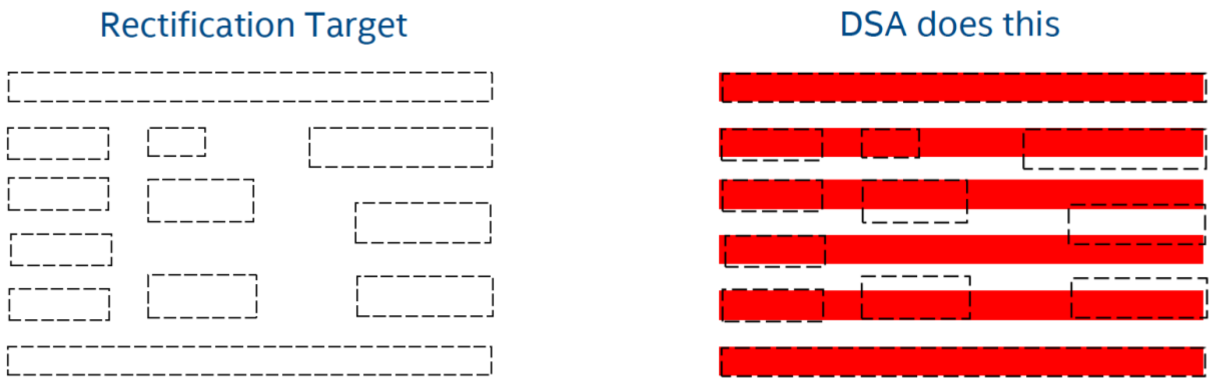

Fig. 11. Diagram showing how DSA does not preserve the target layout, so there is a need for pitch-independent rectification of roughness and defects. Image Credit: Intel

2.4.2. EUV Collector Mirrors: Tin ions, vapor, and particle characterization

Patterning with EUV light brings a host of new challenges as most materials strongly absorb 13.5 nm radiation. This requires that light be generated and guided in a vacuum using mirrors rather than lenses due to strong material interactions. The initial plasma light collection mirror is concave and ellipsoidal, with the plasma generated at the first focus. At the second, or intermediate, focus the plasma light is guided towards exposure tools (Fig. 12). Wavelength matching across the entire collection area and IR spectral filtering are key features in the multilayer collector mirror.

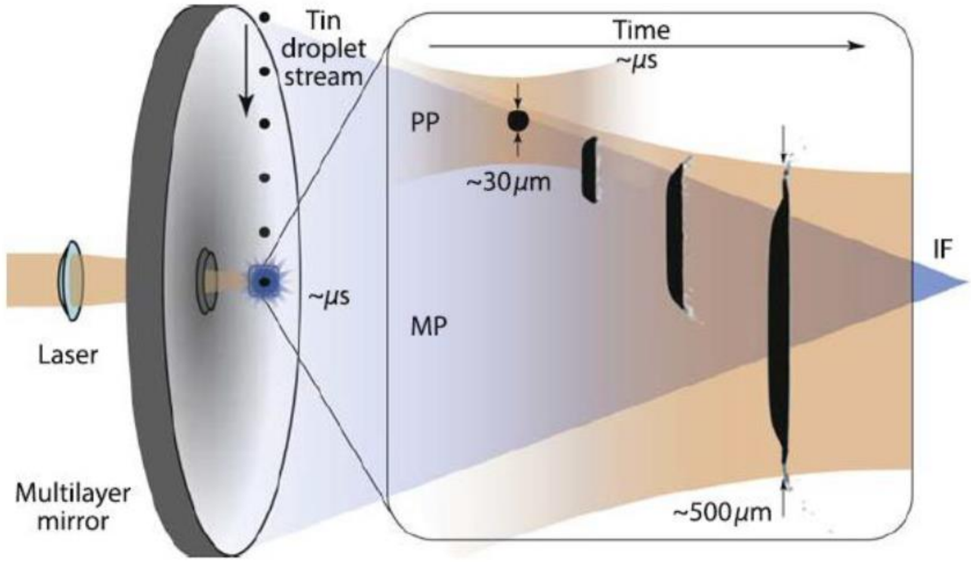

Fig. 12. Diagram showing the concept of EUV collected with near-normal incidence multilayer mirror. Image Credit: Versolanto [46]

Moreover, generating sufficient quantities of EUV radiation is extremely difficult, so efforts must be taken to ensure that mirrors are of the highest possible reflectivity and spatial uniformity. Furthermore, the multilayer mirror's reflectivity must remain high over the period of operation of the lithographic tool. The lithographic process involves exposing the pattern to a photoresist that stores the pattern for further processing (Sec. 2.4.1). The EUV radiation causes chemical changes in the photoresist, which creates volatile compounds that may migrate through the vacuum system and can be adsorbed onto surfaces. Although photoresists can impact mirror surfaces, it is not a major concern for the collection mirror. Industry members stated that the two primary debris types affecting the collection mirror are (1) debris directly from the plasma where heat and momentum transfer into surrounding buffer H_2 gas; and (2) before a collision with any surface, a tin flux that goes into a collector and consists of (i) diffusion of stopped ions, (ii) tin vapor, and (iii) tin micro-particles.

The current method used to protect the collector mirror from debris is by hydrogen flow [59]. A hydrogen buffer gas of about 100 Pa causes the deceleration of ions [60]. The hydrogen flows away from the collector, which reduces the atomic tin deposition rate onto the collector. The reaction of H radicals with tin forms stannane (SnH_4), which can be pumped away according to the reaction shown in Eqn. 1.

$$\mathrm{Sn}\ (s) + 4\mathrm{H}\ (g) \longrightarrow \mathrm{SnH_4}\ (g) \tag{1}$$

The pumping action that takes place in a vessel with vacuum pumping to remove hot gas and tin vapor also aids in protecting the collector mirror. In addition, internal hardware collects microparticles. Cleaning of the mirror has been investigated by industry to address contamination [61]. The efforts by industry to improve the collector mirror's lifetime have led to improvements, specifically over 6-month lifetime was demonstrated in 2021 [62].

Even with these substantial improvements to protecting the EUV collector mirror, two needs were expressed by industry members. First, understanding, "How do photons and plasma species interact with the background gas, optical, and plasma facing surfaces in the EUV source?" Limiting knowledge gaps include secondary plasmas and their interactions, transmission and spectra, plasma-radiation-wall physical chemistry, and plasma diagnostics. Second, understanding "What happens to tin and how can it be managed?" Knowledge gaps here include tin contamination, hydrogen radical cleaning of tin, stannane formation process plus related heat and mass transport and chemistry, small particle detection.

2.5. EUV Light as an Analysis Tool

At the working group meeting, three topics were discussed by NIST researchers about using EUV as an analysis tool to assist the semiconductor manufacturing industry. The three ways of using EUV light as an analysis technique are (1) high-harmonic generation (2) synchrotron (3) atom probe tomography. The high-harmonic generation has a compact footprint allowing for deployment at R&D and fabrication facilities and continuous access to dimensional, material, and dynamic properties in microelectronic devices at the deep nanoscale routinely performed at synchrotron light sources. Synchrotron light sources allow for studies of many aspects of EUVL with the additional capability of studying collector mirror degradation. Atom probe tomography is the only 3D chemical mapping technique able to provide sub-nm isotopically resolved atomic-scale elemental maps of any element on the periodic table, which could be useful to study EUV photoresists.

Industry provided valuable feedback on these tools' potential use in assisting their EUVL manufacturing. NIST legal council must act proactively to develop a solution to NDA requests that satisfies potential collaborators while fulfilling the unique legal and administrative requirements born by federal staff who are explicitly forbidden from obligating themselves or the organization to any external contract.

2.5.1. High-harmonic generation (HHG)

As EUVL pushes lithographic features further into the deep nanoscale regime, the microelectronics industry is calling for new measurement and metrology techniques. At NIST there is an ongoing program that exploits the short wavelength of EUV to probe the dimensional, material, and dynamic properties in microelectronic devices at the deep nanoscale. The high-harmonic generation (HHG) light source at NIST is broadband (spanning 20-100 eV photon energies), ultrafast (20 femtosecond pulses), and coherent (laser-like). The broadband spectrum enables access to atomic core transitions in many relevant materials for microelectronics – revealing element and layer-specific measurement. This is demonstrated in Fig. 13. Such measurements are routinely performed at synchrotron light sources. However, the compact footprint of the HHG source allows for deployment at R&D and fabrication facilities and continuous access. Fig. 14 shows a photograph of the current system operation at NIST of the Physics Material Laboratory (PML), which fits into a typical lab space.

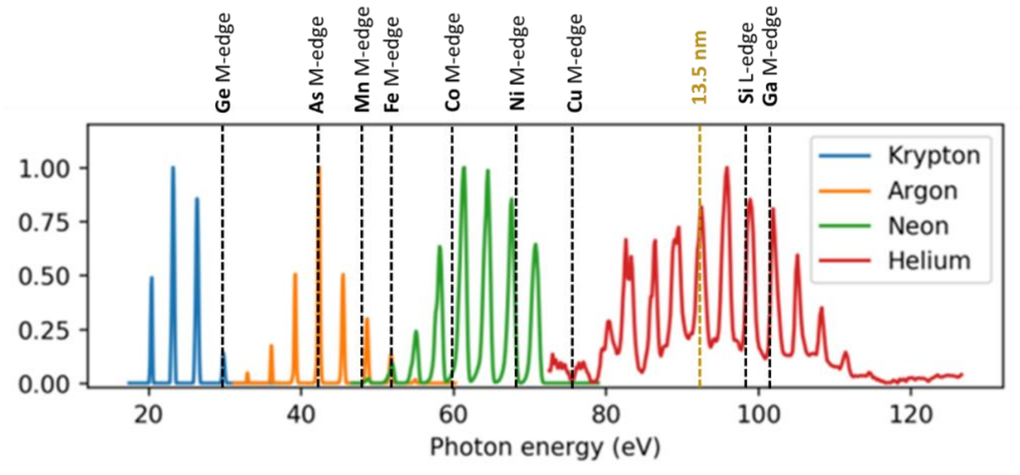

Fig. 13. Output spectrum of the photon energies from the NIST high-harmonic generation source with the location of several atomic core level transitions in relevant materials.

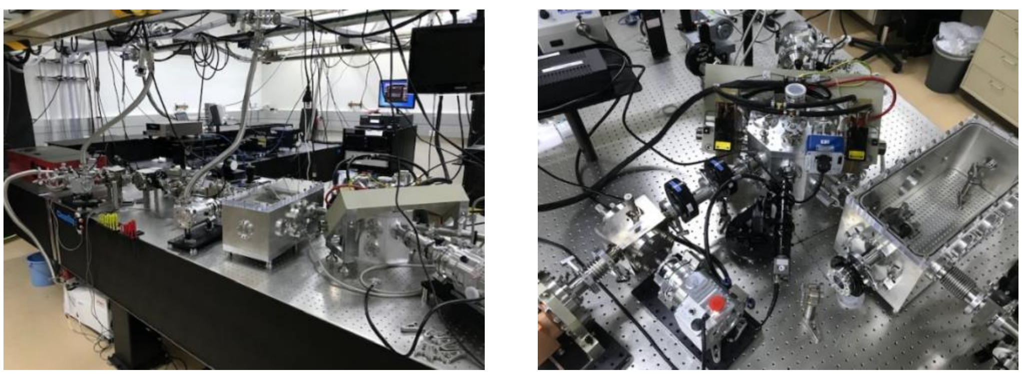

Fig. 14. Photograph of an HHG source and instruments attached to it at NIST.

The short pulse width enables dynamic measurements of spin and thermal transport. A recent success was the development of a frequency comb generator synchronized to the EUV pulses with jitter better than two picoseconds. Fig. 15 demonstrates this synchronization to a 40 GHz signal. This is approximately an order of magnitude better than what can be achieved at synchrotrons and allows our measurements to be performed at the operating frequency of microelectronics devices. This enables real-time measurement of heat flow and spin transport within and out of a functioning device.

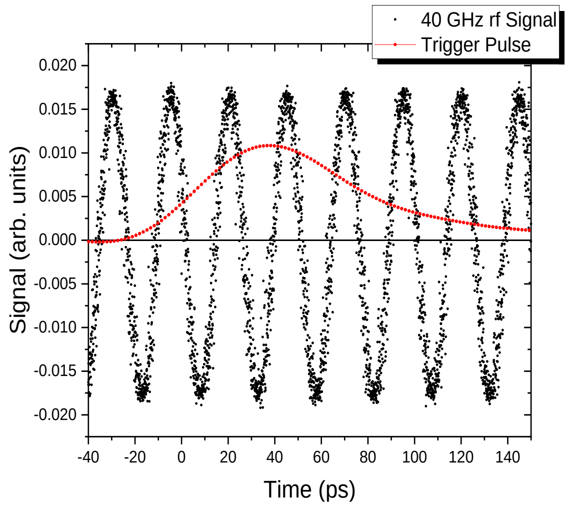

Fig. 15. A 40 GHz signal on a sampling oscilloscope. The trigger pulse (red) came from the pulse used in the HHG system, directly showing the synchronization of the HHG and the 40 GHz signal.

Finally, the coherence of the light enables lens-less imaging techniques such as coherent diffractive imaging, ptychography, and holography that provide spatial resolution at the wavelength of the EUV. This capability will enable NIST to directly image functioning devices. Although this work was not done at NIST, Fig. 16 shows a result of combining ptychography with reflectometry to measure dopant profiles in silicon with lateral spatial resolution. Such approaches allow for a non-destructive evaluation of interface and dopant profiles in microelectronics.

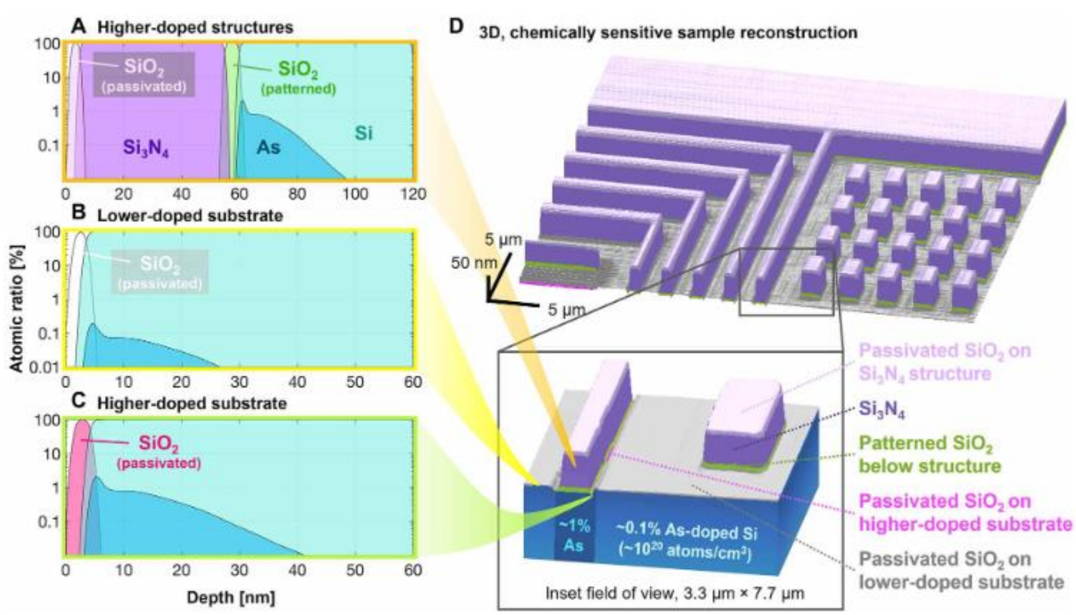

Fig. 16. Example of 3D nanoscale characterization of dopant profiles using a combined reflectometry and ptychography technique. Image from Tanksalvala *et al.* [63]

In the working group meeting industry mentioned how analyzing semiconductor components in wafers to identify defects has been useful. Specifically, Golani *et al.* recently showed how using simulations that separated light-structure interaction simulation from the optical system simulation, performing the latter in post-process, enabled many optical configurations to be tested in a relatively short time [64]. The simulations by Golani *et al.* were completed using Ansys commercial solver and showed the use of a robust digital twin.

2.5.2. Synchrotron: NIST's SURF III

In addition to NIST's lab-scale EUV light to analyze semiconductor components, the large resource of the NIST synchrotron ultraviolet radiation facility (SURF III) was presented by Dr. Steve Grantham at the working group meeting.

Synchrotron radiation is emitted when charged particles travel in curved paths. Since most accelerators use magnetic fields to bend the particle trajectories, synchrotron radiation is also called magneto-bremsstrahlung. The emitted spectrum is broadband from the microwave (harmonics of the driving RF field) to X-ray spectral regions. The radiation is vertically collimated and polarized. The synchrotron radiation output can be calculated if the electron energy E, bending radius ρ, electron current I_B, the angle relative to the orbital plane Ψ_0, the distance to the tangent point d, and vertical $\Delta\psi$, and horizontal acceptance $\Delta\theta$, angles are known. The output power of SURF is illustrated in Fig. 17.

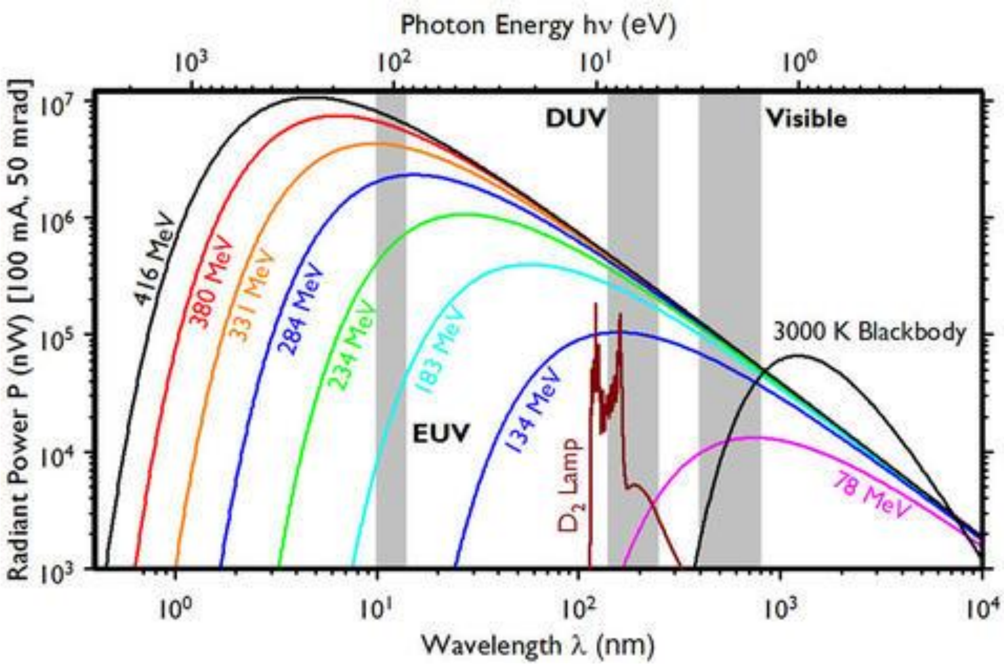

Fig. 17. Synchrotron Radiation Spectrum emitted by SURF at 416 MeV, 380 MeV, 331 MeV, 284 MeV, 234 MeV, 183 MeV, 134 MeV, and 78 MeV in comparison to a 3000 K blackbody and a deuterium lamp.

In turn, NIST's Ultraviolet Radiation Group operates SURF III as a stable light source for radiometry and research. SURF covers the wavelength range from the far infrared to the soft X-ray. Table 1 shows an outline of the NIST SURF III's current capabilities and future plans for beamlines. Industry noted that a synchrotron source is not applicable as a EUV light source in high-volume manufacturing (HVM) environments. Nevertheless, a synchrotron facility could be advantageous, given its flexibility in testing many parameters to assist the HVM goals of the EUVL industry, as discussed in prior sections of this report (2.2 and 2.4.2). It should be noted that the definition and terms for systems at certain wavelengths overlaps and can be inconsistent, thus the ISO 21348 standard should be referenced for general guidelines [65].

Table 1. Synchrotron beamlines at NIST's SURF III current capabilities and future plans.

Beamline Number	Current Capabilities	Future Plans
1	Properties of EUV Photoresists plus EUV Multilayer Degradation Studies	
2	Absolute Source-Based Irradiance Calibrations of Radiometric Instrumentation	
3	Ultraviolet Lamp Calibrations	Adding ACR to expand the range of working standards. Make permanent home for the new ACR on Beamline 4 so ACR operation is available
4	Ultraviolet and EUV Optical Properties and Calibrations	
5	Ultraviolet Optical Properties and Calibrations	
6	New Beam Imaging System	
6B	Current Monitor	
7	Educational Display	Upgrade Monochromator, New Reflectometer
8	EUV Optical Properties and Calibrations	
9	EUV Multilayer Endurance Testing	
10	Infrared Spectromicroscopy	

In the working group meeting, an example of studying contamination of mirrors when illuminating with EUV radiation in the presence of contaminating and/or cleaning species was given. NIST has been a leading center in studying EUVL optics contamination since 2000 and has investigated the degradation of filters commonly used in satellites. More recently, the NIST Sensor Science Division has executed similar studies on semiconductor manufacturing applications [66-68]. NIST currently has three facilities on two beamlines (Beamline 1 and Beamline 8) devoted to various aspects of optics contamination. The ability to study contamination directly relates to the discussion on the importance of increasing the life of collector mirrors earlier in this report (Sec. 2.4.2). Support would be needed to continue and grow the current facilities to support this next generation of EUVL manufacturing for the semiconductor industry.

2.5.3. Atom Probe Tomography (APT)

Atom probe tomography (APT) is the only 3D chemical mapping technique able to provide sub-nm isotopically resolved atomic-scale elemental maps of any element on the periodic table. In Fig. 18, a diagram of the APT operation is given, for further background information on APT the reader is pointed to a recent review on the topic [69].

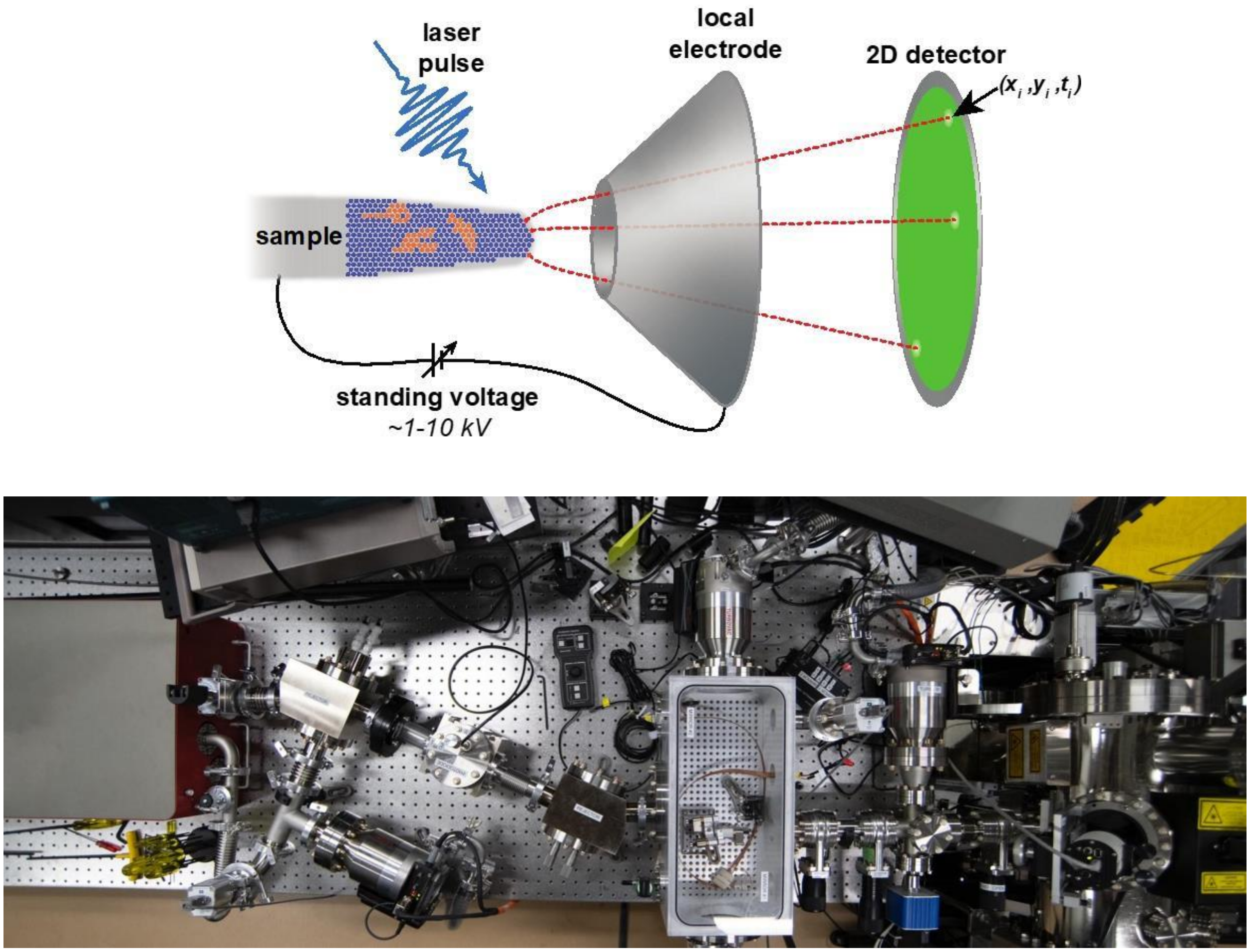

Fig. 18. Atom probe tomography (APT) (top) schematic of the operation (bottom) photograph of the APT located at NIST in Boulder, CO. Image Sources: NIST

Commercial APT instruments employ near ultraviolet (NUV: 3.5 eV) or deep ultraviolet (DUV: 4.8 eV) laser radiation, which is below the work function of many materials and the ionization energy of most elements. Thus, these instruments will likely operate via bulk heating of the specimen under study. Indeed, for the analysis of organic materials, data from NUV instruments are often complicated, showing problematic fragmentation patterns, evidence of polymerization during the field evaporation process, and results that are not directly interpretable into atom-scale maps. In contrast, EUV (20-90 eV) radiation is sufficiently energetic to ionize atoms and molecules at the specimen surface, potentially producing smaller, directly interpretable fragmentation patterns. The NIST approach is to adapt EUV APT to the study of thin film photoresists to look for nanoscale composition fluctuations that may contribute to the stochastic nature of photolithographic irregularities, including LER [70]. Thus, EUV APT represents a critical metrology advancement in studying stochastic events associated with photoresist processing and compositional chemistry (Sec. 2.4.1). Notably, this approach, as well as work discussed in earlier Sec. 2.3, will compare results between EUV APT and conventional NUV and DUV APT instruments.

3. Findings and Recommendations

The technical findings from the working group meeting are included at the end of each subsection in Sec. 2 of this report. Experimentation to extract critical properties would foster modeling and simulation techniques that drive the semiconductor's high yield, throughput, and scaling. NIST has a unique experimental metrology skillset and theoretical simulation programs for EUVL. Thus, funding the NIST proposed efforts that create instruments or use current instruments to provide ultra-accurate data to the US industry was encouraged by industry attendees of the working group meeting. As possible, NIST scientists should not be design engineers for industry but, through collaboration, should use their domain knowledge paired with insights into EUVL for mutually beneficial outcomes. In turn, knowledge transfer must be aligned with the mission of the funding. Industry has methods to support domestic interests, but NIST scientific and management leaders must understand how to align any newly created competitive advantage accordingly. Established methods for controlled dissemination, like CRADAs, SRD, and SRMs, should be considered.

From a program perspective, the working group meeting highlighted how the internationally competitive landscape of EUVL leads to non-disclosure agreements (NDAs) being required to have deep technical conversations with NIST researchers. Thus, it was recommended by all working group meeting participants that the NDA process between NIST researchers and industry be streamlined with a turnaround time of under 2 months from the project initiation. Education should be given to NIST staff and management about the NDA process to execute steps correctly.

Finally, from this working group meeting, the value of in-person interactions yields productive conversations and actionable next steps. Future stakeholder interactions could transition from working group meetings *to* workshops *to* consortiums. With increased formality, there is increased cost ($10k - $100k+) and effort (40 – 200+ hours). Therefore, allocating future events at commonly attended professional conferences, for example, meetings of SPIE or the Optical Society of America (OSA), could help mitigate cost and effort.

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Uncategorized References

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Appendix A. List of Speakers

A.1. Speakers

The table below lists the 13 speakers at the April 2023 NIST-hosted EUVL working group meeting.

Name	Affiliation	Session
Marla Dowell	NIST, CHIPS R&D Metrology Program	Keynote 1
Alexander Schafgans	ASML	Session 1: Industry
Jayson Stewart	ASML	Session 1: Industry
Len Orlando	ANSYS	Session 1: Industry
Chris Hill	ANSYS	Session 1: Industry
Florian Gstrein	Intel Corp.	Session 1: Industry
David Wallace	MicroFab Technologies	Session 1: Industry
Stephanie Hooker	NIST	Keynote 2
Elizabeth Rasmussen	NIST	Session 2: NIST Research
Yuri Ralchenko	NIST	Session 2: NIST Research
Steve Grantham	NIST	Session 2: NIST Research
Brian Simonds	NIST	Session 3: NIST Lab Tours
Justin Shaw	NIST	Session 3: NIST Lab Tours

A.1.1. Speaker Biographical Information

Marla Dowell is a multidisciplinary leader who has made broad contributions to the fields of physics and engineering. Today, she serves as director of the CHIPS R&D Metrology and NIST Boulder Laboratory. At NIST, Marla has formed private-public partnerships to advance the underlying measurements to guarantee worldwide availability, reliability, and security of critical emerging technologies, expanded STEM workforce development opportunities, and been a champion for diversity, equity, and inclusion initiatives. Marla's service to NIST has been recognized by several awards, including Department of Commerce Silver Medal, Allen V. Astin Award, and Arthur S. Flemming Award. Marla has degrees in physics from University of Michigan and M.I.T., as well as a M.B.A. from the University of Colorado Boulder.

Alexander Schafgans is Sr. Director of EUV Source Engineering at ASML, the global leader in EUV photolithography tools used in the production of advanced logic and memory. In his current role, Schafgans is responsible for overseeing engineering execution across most Source technology areas, as well as ensuring the performance of all world-wide EUV sources meet or exceed customer expectations, while driving knowledge creation to solve the most persistent and challenging performance problems facing the EUV source products. In his previous roles over his 11 year tenure at ASML, Schafgans was focused on leading EUV power scaling activities from 10W through 500W, resulting in the successful introduction of EUV for High Volume Manufacturing. Alex is a graduate of UC San Diego, with B.S, M.S. and Ph.D. in Physics.

Jayson Stewart serves as Technical Manager in the EUV Source Technology Development Program at ASML in San Diego. Jayson joined the ASML team in 2012 with research interests in light-matter interactions and applications to EUV light source development. He now leads efforts in Research related to tin such as generating tin droplets and managing the debris resulting from the laser produced plasma. Jayson received his PhD in Physics from the University of Colorado in 2009 where he studied ultra-cold atoms.

Len Orlando joined the Ansys team in January of 2023 after serving 21 years with the Air Force Research Laboratory Sensors Directorate. In his AF role, Mr. Orlando was contributing to the DAF Microelectronics Strategy as the lead for LOE4 Modernization and Workforce. His primary focus was to provide a strategy to utilize Mission Scenario Driven Digital Engineering techniques to enable intelligent decision making for insertion of advanced technologies across the DAF lifecycle. This included a comprehensive recruitment, retainment, and upskilling strategy to address the AF current and future capability needs. During his tenure with the Air Force Mr. Orlando developed next generation EW/SIGINT components in FDSOI, SiGe, GaN, InP, and CMOS technologies. Served as a member of the DARPA Independent Verification and Validation Government team supporting multiple Integrated Circuit, EDA, and Security programs. Today, Mr. Orlando focuses on creating strategic alignment and develop opportunities within the Federal, Aerospace, and Defense business unit within AGI, the United States national security division of Ansys, for Ansys solutions within Microelectronics, Digital Engineering, and Security domains.

Chris Hill has a B.Sc. in Physics and Mathematics from the University of Glasgow, Scotland, and a Ph.D. in acoustics from the University of Cambridge, England. He was a post-doctoral researcher at NASA Ames Research Center, and a Senior Fellow in flow control at Stanford Center for

Turbulence Research. Dr. Hill worked on boundary layer stability, receptivity, and control. He is the original author of the Adjoint Solver in Ansys Fluent and has expertise in optimization, mesh morphing, lattice Boltzmann methods, and machine learning applied to CFD. He is an Ansys Fellow and Chief Technologist for fluids.

Florian Gstrein is the director of the EUV Lithography and Novel Materials Research Group at Intel Corporation, and has been at the forefront of semiconductor process technology research for nearly two decades. His expertise encompasses a wide range of fields, including metallization, dielectrics, interconnect reliability, patterning and lithography. In his current role, Florian is responsible for all aspects of next-generation lithography research at Intel, with a particular focus on developing photoresist and underlayer materials for high-NA EUV lithography and innovative patterning solutions based on directed self-assembly and selective deposition. His work has been recognized with two Intel achievement awards, one for the invention of a novel interconnect material and a second award for a novel EUV lithography integration scheme. Florian holds a Master of Science degree in Materials Science from the University of Leoben, Austria and the Max Planck Institute for Metals Research, Stuttgart, Germany and a Ph.D. in Inorganic Chemistry from Caltech. With over 120 issued and filed patents, more than 20 peer-reviewed articles, and numerous keynote presentations at international conferences, he is deeply committed to advancing the field of semiconductor technology and driving innovation in this industry.

David Wallace is Vice President of MicroFab Technologies, Inc., a small business in Plano, Texas that develops technology, equipment, and industrial / medical, and scientific applications of inkjet printing technologies, including: medical diagnostics (~$6B of production to date); drug coated stents; printed optics; aroma generation for VR; vapor generation and printed coupons for trace vapor sensor calibration (drugs, explosives); sensor manufacturing; display front and back panels; and cryogenic fluid and liquid metal droplet generation for EUV. Dr. Wallace has 40 years of experience in inkjet technology (plus a couple in torpedo design). He is a named inventor on 26 patents and author on over 80 papers. He is a fellow of ASME, advisor to two engineering departments and one college of engineering, and has served on Ph.D. and Masters committees at three institutions. Dr. Wallace has been PI on grants and contracts from NSF, NIH, DARPA, DOD, and NIST totaling ~$5M to MicroFab. Three of the projects involved industry consortiums, one of which was organized and lead by MicroFab.

Stephanie A. Hooker is the Acting Director of the Material Measurement Laboratory (MML) at the National Institute of Standards and Technology (NIST). She holds a Ph.D. in Ceramic Engineering from Clemson University, with a minor in Analytical Chemistry. She began her career at NASA developing detector technology for atmospheric sensing, leading the development of a spaceflight experiment that demonstrated first-of-its-kind superconducting electronics and cryocooler technology in space. From 1998-2002, she served as Business Development Manager for Nanomaterials Research, LLC, a startup company developing both nanoparticle technology and nanostructured devices. During that time, she secured venture capital investments, large partnerships with Fortune 500 companies, and exclusive licensing to spin out two new businesses in the nanotech space. Since joining NIST in 2002, she has served as Group Leader, Division Chief, Program Director, Associate Director (MML), Acting Deputy Director (MML), and, most recently Acting Director (MML). She has led programs in nanotechnology, impact-resistant materials for head health, and plastics recycling, as well as being a founding member of NIST's diversity and inclusivity strategy development.

Elizabeth Rasmussen is a National Research Council (NRC) Postdoctoral Fellow at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. Previously she worked in industry as an engineer at Johnson Controls, Kimberly-Clark, and Leviton Network Solutions. Dr. Rasmussen has also been a visiting researcher at MIT Lincoln Laboratory, the National Renewable Energy Laboratory, and Argonne National Laboratory. She received a B.S. from Michigan Technological University and M.S. and Ph.D. degrees from the University of Washington-Seattle, all in mechanical engineering. She has theoretically and experimentally investigated thermophysical properties' usefulness in sustainable and scalable nanomaterial synthesis with emphasis on supercritical CO_2 near the critical point. She currently works on the speed of sound metrology of materials in extreme environments and developing fundamental thermodynamic equations of state. In addition to her research, Dr. Rasmussen serves on the Early Career Board of the American Chemical Society's Journal of Chemical and Engineering Data, is a technical reviewer for several journals, has been an invited technical reviewer for NASEM workshops, is a co-inventor of eight patents, has given over 30 invited technical presentations, and has mentored over 15 undergraduate and graduate students.

Yuri Ralchenko is the Leader of the Atomic Spectroscopy Group at NIST. His research is focused on spectroscopy of highly-charged ions, analysis of various atomic processes in plasmas with emphasis on accurate modeling of plasma population kinetics, development of Internet atomic databases, and other aspects of plasma and atomic spectroscopy. This work includes collisional-radiative modeling of various plasmas (including non-Maxwellian and transient ones), production and assessment of accurate atomic data (energies, oscillator strengths, collisional cross sections, etc.), and development of methods and standards for uncertainty quantification and dissemination of scientific data. Dr. Ralchenko is an Editorial Board member of several scientific journals, has authored over 140 scientific publications, and has been a speaker at numerous national and international conferences. He also is a frequent consultant at the International Atomic Energy Agency (IAEA) and a co-director of a series of Schools on atomic and plasma spectroscopy organized jointly by IAEA and the International Centre for Theoretical Physics in Trieste, Italy.

Steve Grantham received his Ph.D. from the University of Central Florida's Center for Research and Education in Optics and Lasers (CREOL). His graduate research involved the study and application of short pulse laser produced plasmas. He is currently in a lead role of the NIST Physical Measurement Laboratory's team for the development of the Additive Manufacturing Metrology Testbed (AMMT) and the Temperature and Emittance of Melts, Powders and Solids (TEMPS) system.

Justin Shaw is a project leader in the Spin Electronic Group at NIST. His current research focuses on developing and applying new measurement techniques based on optical, microwave, and ultra-fast extreme ultraviolet (EUV) radiation sources to study spin and phonon dynamics in thin films, nanostructures, and devices. He earned bachelor's degrees in both materials science engineering and music theory & composition in 1997, and doctoral degrees in physics in 2004 and in materials science engineering in 2007, all at Arizona State University. He was a National Research Council postdoctoral fellow at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, from 2005 to 2007. In 2007 he became a staff scientist at NIST. He received a U.S. Department of Commerce Bronze medal in 2013 for his work in magnetodynamic measurements of nanostructures and was an IEEE Distinguished Lecturer in 2019.

A.2. List of Participants

The table below lists the 19 participants who were not designated speakers but participated in the April 2023 NIST-hosted EUVL working group meeting.

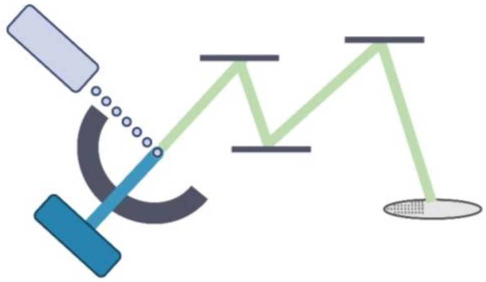
Name	Affiliation
Mark Musitano	ANSYS
Jacob Gantz	ANSYS
Ed Dodd	ANSYS
Evan Fader	ANSYS
Chris Hill	ANSYS
Boris Wilthan	NIST
Joseph Kline	NIST
Luis Miaja	NIST
Norman Sanford	NIST
Jacob Garcia	NIST
Mark McLinden	NIST
Benjamin Caplins	NIST
Jacob Wisser	NIST
Matthew Spidell	NIST
Michael Tanksalvala	NIST
Hans Nembach	NIST
Charles Tarrio	NIST
Robert Vest	NIST
John Perkins	NIST

Appendix B. List of Acronyms

List of Acronyms	
AI	Artificial Intelligence
ASG	Atomic Spectroscopy Group
APT	Atom probe tomography
BIS	Bureau of Industry and Security
CO_2	Carbon dioxide
CHIPS	Creating Helpful Incentives to Produce Semiconductors
CR	Collisional-Radiative
CRADA	Cooperative Research and Development Agreement
CTL	Communications Technology Labratory
DSA	Directed self-assembly
DUV	Deep Ultraviolet
EoS	Equation of state
EBIT	Electron beam ion trap
EPE	Edge placement error
EUV	Extreme ultraviolet
EUVL	Extreme ultraviolet lithography
HHG	High-harmonic generation
HVM	High Volume Manufacturing
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
IRDS	International Roadmap for Devices and Systems
LER	Line-edge roughness
MGI	Materials Genome Initiative
MML	Material Measurement Labratory
MTA	Material transfer agreements
NA	Numerical aperture
NDA	Nondisclosure Agreement
NIST	National Institute of Standards and Technology
NLTE	Non-local thermodynamic equilibrium
NRC	National Research Council
NUV	Near Ultraviolet
PNNL	Pacific Northwest National Labratory
R&D	Research and Development
REFPROP	REFerence fluid PROPerties
SADP	Self aligned double patterning
SRD	Standard reference data
SRM	Standard reference material
SoS	Speed of Sound

Appendix C. Working Group Meeting Agenda

Below is the agenda that was used for the working group meeting.



Extreme Ultraviolet (EUV) Lithography Working Group Meeting: Current State, Needs, and Path Forward

Working Group Chair: Elizabeth Rasmussen

Hosted by NIST’s Material Measurement Laboratory Applied Chemicals and Materials Division

Tuesday, April 25, 2023
Katherine Blodget Gebbie Building (81) of the National Institute of Standards and Technology
325 Broadway, Boulder, CO 80305

<table>
<tr><td>9:00 AM MT</td><td><u>Welcome and Introductions:</u>

Marla Dowell
Director, CHIPS R&D Metrology Program
CHIPS for America, U.S. Department of Commerce</td></tr>
<tr><td colspan="2">Industry Presentations: 20 min. Talks | 10 min. Discussions | 5 min. Transitions</td></tr>
<tr><td>9:15 AM MT</td><td>Alexander Schafgans
Sr. Director, EUV Engineering
ASML

Jayson Stewart
Technology Manager, EUV Source
ASML

EUV Sources for HVM: Performance & availability in the field, & innovation towards the future</td></tr>
</table>

9:50 AM MT	**Len Orlando** Senior Business Development Executive Ansys Simulation **Chris Hill** Chief Technologist of Fluids Ansys Simulation *Multi-Physics Digital Twin for EUV Lithography applications*
10:25 AM MT	**Florian Gstrein** Director, EUV Lithography & Novel Materials Research Group Intel Corporation *Material and Patterning Innovation: The Foundation for Moore's Law Extension*
11:00 AM MT	**David Wallace** Vice President MicroFab Technologies *Rayleigh Droplet Generation for EUV: from Cryogenic Liquids to Molten Metal*
11:35 AM MT	Industry: Overview of Technical Needs Round Table Discussion
Lunch Break, 12:00 – 1:00 PM MT	
1:05 PM MT	Afternoon Session Introduction: **Stephanie Hooker** Acting Director Material Measurement Laboratory, NIST
NIST Researcher Presentations: 20 min. Talks | 10 min. Discussions | 5 min. Transitions	
1:20 PM MT	**Elizabeth Rasmussen** National Research Council (NRC) Postdoctoral Fellow Thermophysical Properties of Fluids Group Material Measurement Laboratory, NIST *Thermophysical Metrology of Tin Used in Generating the Light Source of EUV Lithography*

1:55 PM MT	**Yuri Ralchenko** Group Leader Atomic Spectroscopy Group Physical Measurement Laboratory, NIST *Validation and Verification of Atomic Data and Plasma Emission Codes for EUV Lithography Sources*
2:30 PM MT	**Steve Grantham** Researcher Remote Sensing Group Physical Measurement Laboratory, NIST *Metrology at Synchrotron Ultraviolet Radiation Facility (SURF III) for EUVL*
3:10 PM MT	NIST: Overview of Technical Needs Round Table Discussion
Break, 3:30 PM MT	
Lab Tours: 5 min. Travel Time to Site | 20 min. Lab Tour | 5 min. Travel Time To Next Site	
3:45 PM MT	*Laser Power Calibration and Photonic Radiometry Laboratory* **Brian Simonds** Sources and Detectors Group, Physical Measurement Laboratory Building 1, Lab: 3317
4:15 PM MT	*Dynamic EUV Imaging & Spectroscopy for Microelectronics Laboratory* **Justin Shaw** Spin Electronics Group, Physical Measurement Laboratory Building 81, Lab: 1D116
4:45 PM MT	Future Work and Path Forward Round Table Discussion
5:10 PM MT	Final Remarks and Recap of the Working Group Meeting: **Elizabeth Rasmussen** National Research Council (NRC) Postdoctoral Fellow Thermophysical Properties of Fluids Group Material Measurement Laboratory
5:15 PM MT	Working Group Meeting Adjourned