Blue -X

making circuit elements smaller!

Blue-X: Exploring Advanced Optical Projection Lithography Below 13.5 nm

(Paper 13979-27, Session 7: Special Session: Future of EUVL, SPIE Advanced Lithography, February 24, 2026, San Jose, CA)

Vivek Bakshi, EUV Litho, Inc.

Blue -X
making circuit elements smaller!

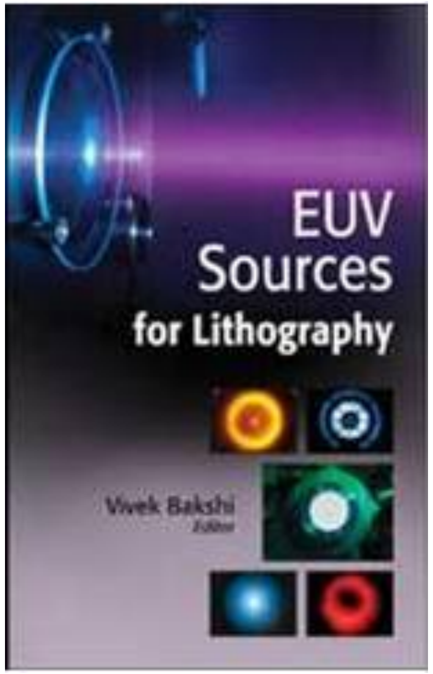
EUV Litho, Inc.

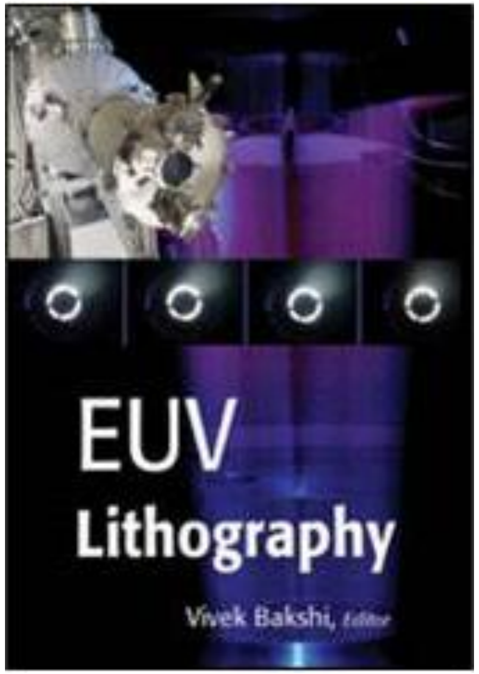
Thanks to many colleagues for the success of Blue-X TWG!

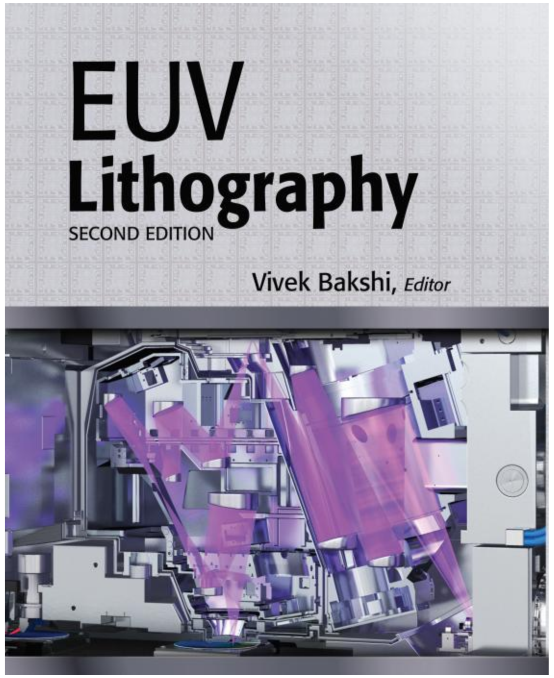
- **Blue-X TWG Members:** Marcelo Ackermann, Julie Bentley, Ibrahim Burki, Antonio Checco, James Colgan, Isvar Cordova, Anuja DeSilva, Ben Eynon, Donis Flagello, **Allen Gabor**, Greg Gallatin, Dario Goldfarb, Eric Gullikson, Hari Harilal, Takeshi Higashiguchi, Hiroshi Kawata, Nicholas Kelez, Meng Lee, Peter Moulton, Iacopo Mochi, Patrick Naulleau, Ladislav Pina, Yuri Ralchenko, Mordy Rothschild, Mark Schattenburg, Sam Sivakumar, Victor Soltwisch, Oscar Versolato, Jackson Williams

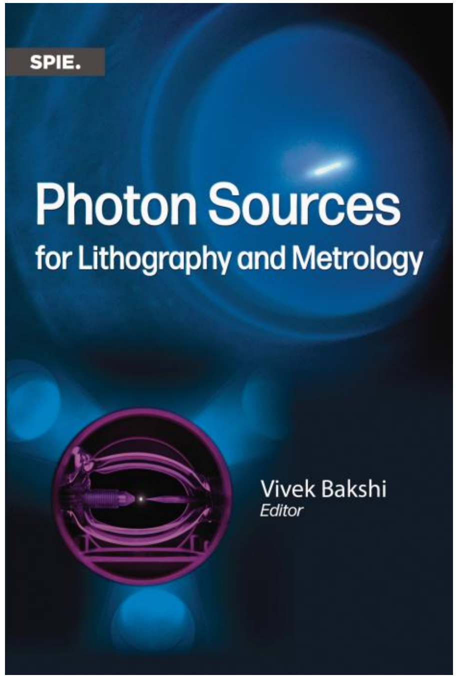
- **CXRO Team** for help on Resist Exposures, ML Development, SHARP for Blue-X design, Dose Partitioning Experiments (Bruno LaFontaine, Markus Benk, **Eric Gullikson, Oleg Kostko**, Ryan Miyakawa)

My Background







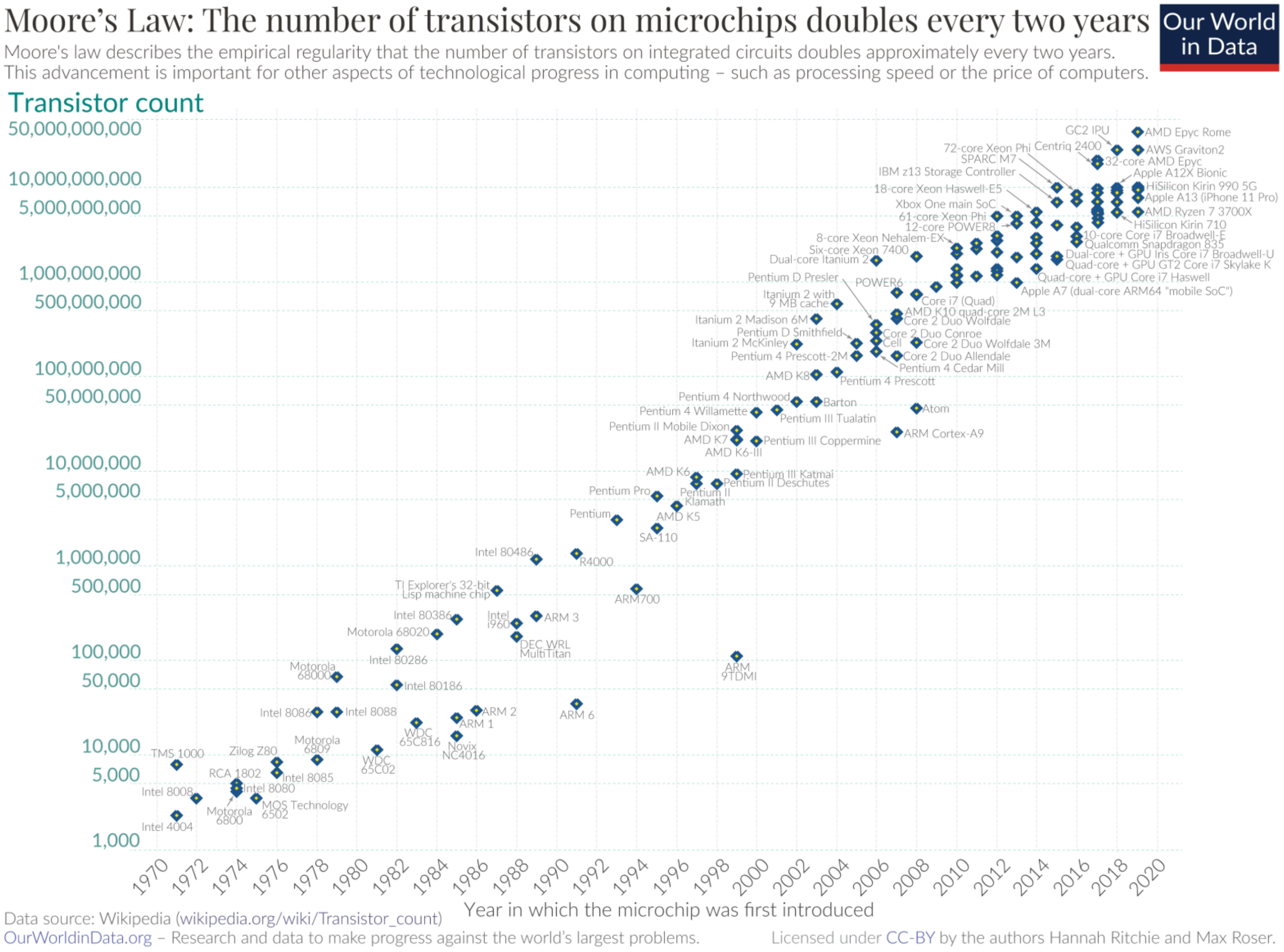


- Edited four EUVL books for SPIE Press
- Organizing annual EUVL Workshop (since 2008) and Source Workshop (since 2003)
- Website www.euvlitho.com is a major resource for EUVL related references
- President, EUV Litho Inc. (2007) and was Senior Member of Technical Staff at SEMATECH

Presentation Outline

- 1. Moore's' Law and Industry Requirements
- 2. Blue-X TWG Consortium: Organization and Membership
- 3. Blue-X TWG Consortium: Technical Projects and Results
- 4. Summary

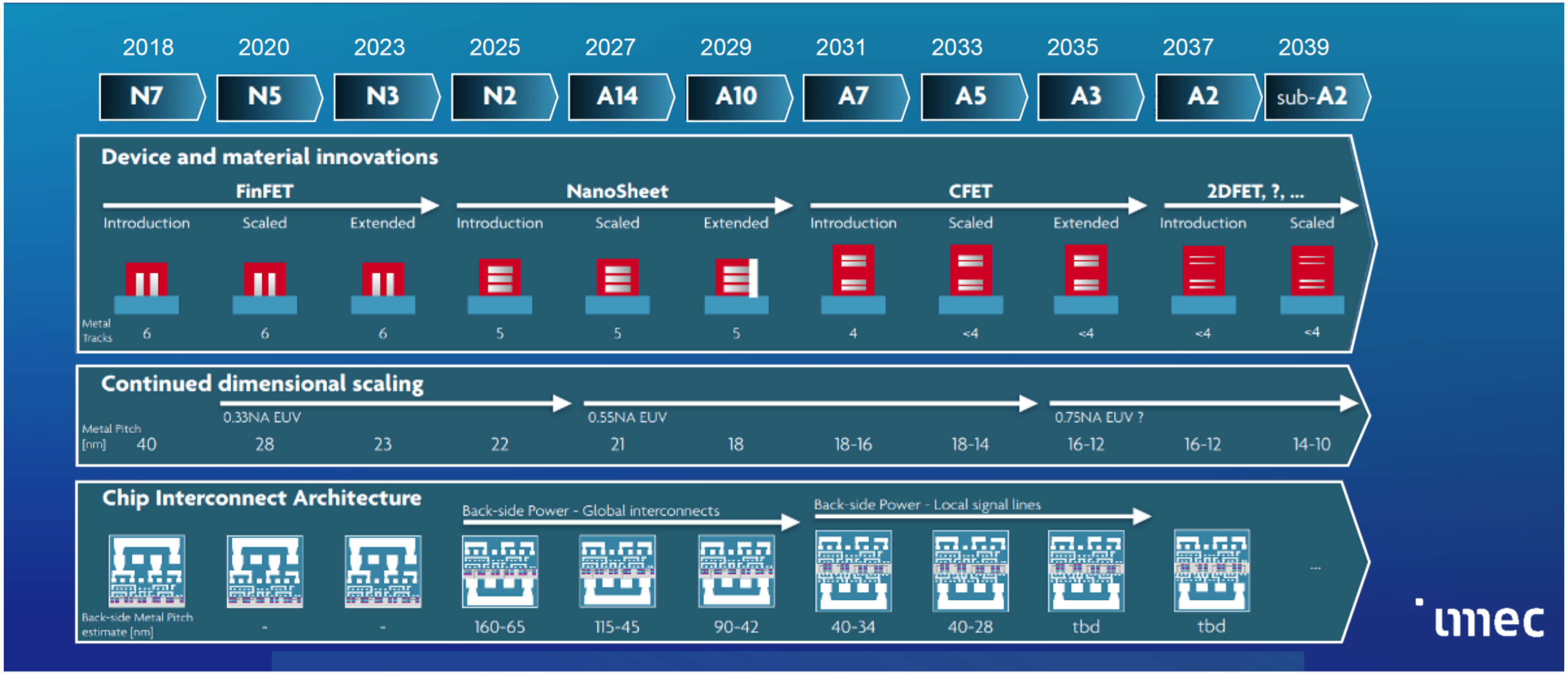
1. Is Moore's Law Dead or Alive or Just Slowed?



1. Industry Roadmap: 5- 7 nm HP by 2039

The logic device roadmap is clearly defined for the next 15 years

The more complex 3D device processing increase the value of shrink



1. Extending Moore's Law Beyond High NA: Two Options

- Extending Moore's law beyond High NA EUVL:
- Two Options
  - 1: Keep the Same Scanner:
    - Lower k1 and then MP
  - 2: New Scanner Technology:
    - Hyper NA: Increase NA to 0.75
    - Blue –X: Reduce wavelength
      - Water-window region (2.1 – 4.2 nm)
        - 6.7 nm was previously explored under the name BEUV

$$Resolution = k1\ \frac{\lambda}{NA}$$

$$DOF = k2\ \frac{\lambda}{NA^2}$$

1. Blue-X: Extending Moore's Law Beyond High NA:
Hyper NA

- Wavelength reduction has been the leading driver of the extension of Moore's Law
- Switch from 193 nm to 13.5 was HUGE and it brought us into a new region of Physics!
- We want to maximize the benefit from these investment and learnings as much as possible
  - Hence, High NA and proposal for Hyper NA
  - However, <u>Blue-X also uses most of the same technology</u>

1. Blue-X: Extending Moore's Law Beyond High NA:
Hyper NA

- With Hyper NA, leading challenges are:
  - DOF, Mask 3D Effects, COO
- Increase of NA, beyond proposed Hyper NA, is not possible
- Industry Roadmap (IRDS) always has multiple technology options for upcoming nodes. Not doing so is very risky for the industry
- Now is the time to explore the "wavelength knob"

1. Patterning Landscape at 7 nm HP

HP (Metal)→		nm ↓	9	8	7	6	5
Year (Plan) →			2029	2031	2033	2037	2040
λ (nm) ↓	NA ↓	DOF (nm) ↓	k1 ↓	k1 ↓	k1 ↓	k1 ↓	k1 ↓
13.5	0.33	124	0.22	0.20	0.17	0.15	0.12
13.5	0.55	45	0.37	0.33	0.29	0.24	0.20
13.5	0.75	24	0.50	0.44	0.39	0.33	0.28
6.5	0.33	60	0.46	0.41	0.36	0.30	0.25
3.1	**0.27**	43	0.78	0.69	**0.60**	0.52	0.43

For 7 nm HP

- **High NA: MP needed**
- **Hyper NA: DOF, COO, Mask 3D effects**
- **6.5 nm: Performance similar to High NA**
- **3.1 nm: OK but need to evaluate technology components – mission of Blue-X TWG!**

2. Blue-X TWG Consortium:

Organization and Membership

EUV
LITHO, INC.

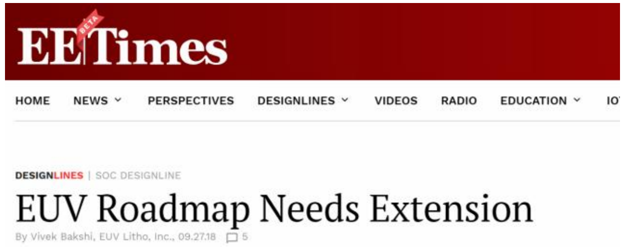
Blue -X

making circuit elements smaller!

1. Blue-X: Extending Moore's Law Beyond High NA:

Value Proposition for Blue-X TWG Consortium: Technology leaders from all technical areas working together to evaluate the system performance of a "Blue-X Scanner (2- 7 nm range)"

- Concept of exploring wavelength reduction, beyond 6.7 nm (BEUV), was first introduced during 2018 Source Workshop in Prague
  - 2 Micron solid-state lasers, Short Wavelength Sources, Code Comparison for modeling of CE
- Consortium launched during 2024 Source Workshop in Amsterdam
  - Blue-X TWG will explore the feasibility, challenges, and potential solutions for implementing projection lithography at < 13.5 nm
  - The TWG will provide a forum for information exchange across disciplines, organizations, and geographic areas
  - Such collaborations are the only way to grow a successful community to solve the difficult challenges ahead!



2. Blue-X TWG: Business Structure

- Effective "low overhead" and pre-competitive consortium model
- Public forum, open only to its members
- EUV Litho / Blue-X TWG will not file for IP in the Blue-X area
  - Members file for their own IP protection, before sharing results with others
- Mostly online meetings and experimental work at leading facilities
  - One annual in-person meeting (June)
  - Quarterly all-hands and frequent sub-TWG meetings (online)
  - Private website, Google drive, and monthly newsletter
- "Very low" membership fee, with "in-kind exchange" possible

2. Blue-X TWG: Business Structure

- Industry-wide recognition and participation
  - Members represent all segments of leading edge litho infrastructure
  - Chip Makers, Large (>100) and Small (<100) OEMS, National Labs, Universities, Independent Consultants
  - Blue-X invited to 2026 SPIE AL ‘Future of EUV’ session – 6 out of 8 papers from Blue-X TWG members
- Membership: >75 members, >220 assignees
- Collaborations, under this type of business model, are an attractive way to grow a successful community to solve the difficult technical challenges!

2.1 Blue-X TWG Members: 68 Organizations / 190 Assignees

January 2025: 75 Org. / 220+ Assignees; Full list available to members. Emails to TWG co-chairs.

- **Chip Makers (2):** IBM, Intel plus informal participation by additional leading chip maker
- **OEMs (32)**
  - AFS, AGC, AlixLabs, Corning, Energetiq, EUV Tech, FS Dynamics, Fujifilm, Hoya, ISTEQ, JSR, LAM, Luxel, Merck/EMD, Mitsubishi Chemicals/Gelest, Nikon Research Corporation of America, optiXfab, Photronics, Prism Computations, Qnity Electronics, Research Instruments, Research Instruments Corporation, Rigaku, Shin-Etsu Microsi, Tekscend, TEL, TOK, Trumpf, USHIO, and Veeco, and xLight
- **National Labs (16)**
  - ARCNL, Brookhaven NL, Fraunhofer IOF, KEK, LANL, LBNL, LLNL, MIT LL, NIST, PAL, PNNL, PSI, PTB, and QST
- **Universities (20)**
  - CH3IP/Hanyang University, Chonnam National University, Hokkaido University, Johns Hopkins, Kyung Hee University, Kyushu University, National Taiwan University, Osaka University, OIST, POSTECH, PPPL, Sungkyunkwan University, Université Paris-Saclay, University College Dublin, University of Albany, University of California at San Diego, University of Hyogo, University of Japan, University of Twente, and Utsunomiya University
- **Consultants (6)**
  - Applied Math, AS Lithography Consulting, Bentley Optical Design, John Carruthers, and others

2. Blue-X TWG: Key to Success - Eleven sub – TWGs

Sub-TWG Chairs (Technology Leaders) are Leading Blue-X Activities!

- **Imaging / Optical Design / Scanner**: Greg Gallatin (Applied Math), Allen Gabor (IBM), Patrick Naulleau (EUV Tech), Donis Flagello (Nikon Research Corporation)
- **Mask**: Meng Lee (Veeco), Ben Eynon (Lam)
- **Metrology**: Isvar Cordova (NIST), Iacopo Mochi (PSI)
- **Optics (ML Optics):** Marcelo Ackermann (University of Twente /ARCNL), Antonio Checco (Veeco)
  - **Optical Constants:** Eric Gullikson (LBNL), Victor Soltwisch (PTB)
- **Optics (Non-ML Optics):** Ladislav Pina (Rigaku), Mark Schattenburg (MIT)
- **Resist and Patterning**: Dario Goldfarb (IBM), Mordy Rothschild (MIT Lincoln Laboratory), Anuja DeSilva (Lam)
- **Photon Sources (Plasma):** Oscar Versolato (ARCNL), Hari Harilal (PNNL), Takeshi Higashiguchi (Utsunomiya University)
  - **Lasers:** Peter Moulton (MIT Lincoln Laboratory), Jackson Williams (LLNL)
  - **Fundamental data:** James Colgan (LANL), Yuri Ralchenko (University of Maryland)
- **Photon Sources (FEL):** Hiroshi Kawata (KEK), Nicholas Kelez (xLight)

3. Blue-X TWG Consortium:

Technical Projects and Results

3. Technical Options to be Explored: 2- 7 nm

- Optics for 2-7 nm
  - ML optics, Optical Constants, Non-ML optics (GI, diffractive optics)
- Photon Sources for 2-7 nm
  - Explore plasma sources and fundamental data, non–plasma sources
- Scanner Design
  - Imaging requirements, general optical design, efficient design
- **Resist**
  - **6.7 nm and 3.1 nm**
- Masks
  - General specs, substrate requirements, ML stacks, absorber and size

3.1 Starting Point: ML Optics in the Water Window (WW) Region

Calculation of WW MLs Cr with Ti, Sc, V, C

IMD calculations

N=1000
(400 minimum)

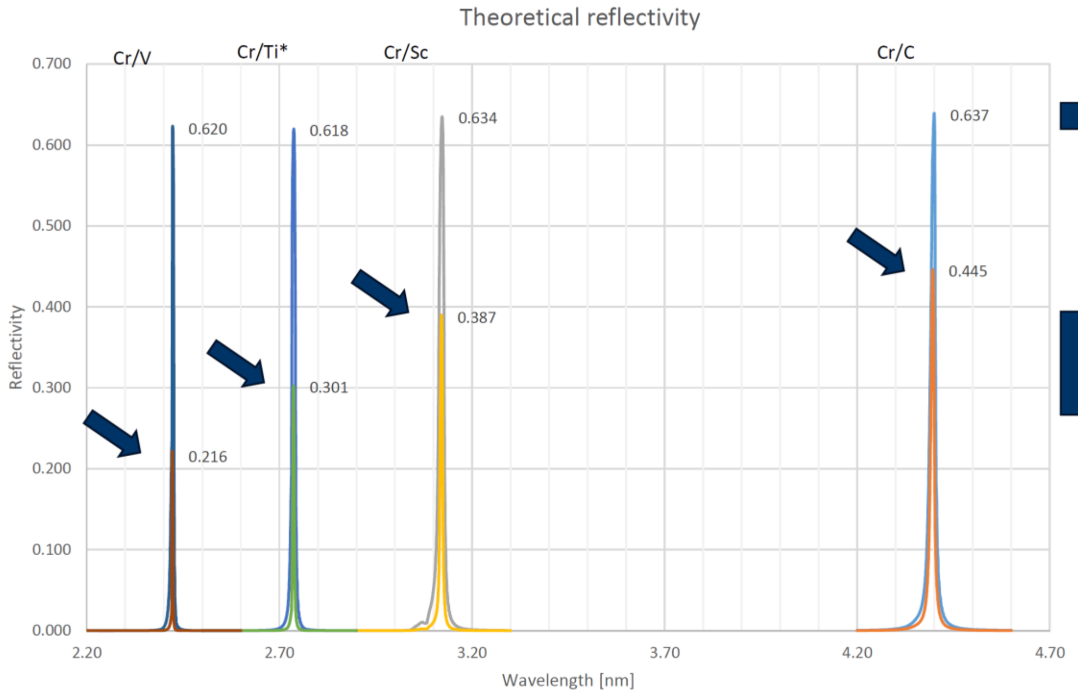
88.5 deg

Sigma (DW) at 0 and 0.3 nm

Bulk density

No barriers

Cr terminated



>60% theoretical

Rapidly decreasing when adding interfacial roughness from 44% (4.4nm) to 21% (2.4nm)

Generally : relfectivity drops faster and faster with realistic ML growth for shorter wavelengths

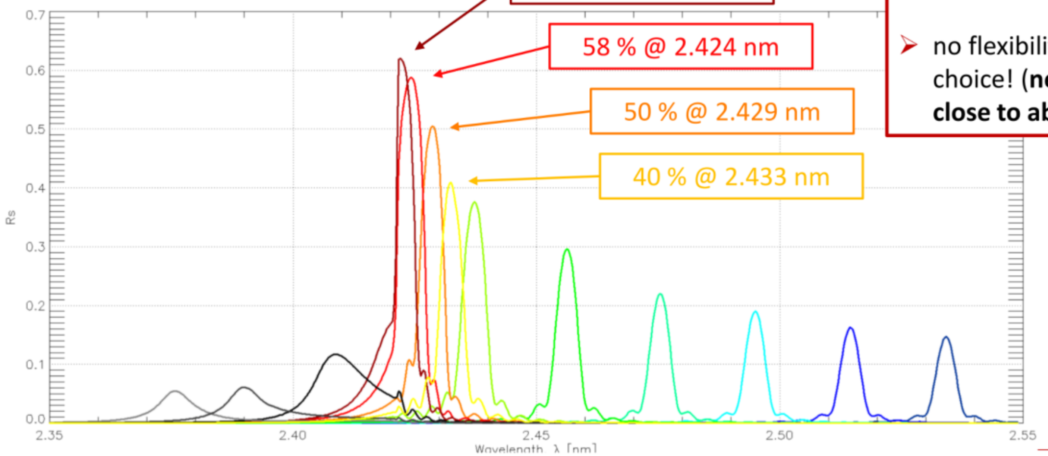
- Reflectivity loss reduces, as interfacial roughness decreases
- Almost linear increase in the reflectivity from sigma at 0.3 nm to 0 nm.

3.1 WW ML Challenges and Potential Solutions

- WW MLs reflectivity curves are very narrow and the peak reflectivity drops very quickly away from the peak (10-20 pm range).
- Plasma source need to be very close to absorption edges! V/Cr ML not suitable for N_2 lines at 2.48 nm. MIT LL has identified alternate ML pairs with theoretical reflectivity ~ 50%.

ML coatings for water window – Vanadium edge

- Vanadium absorption edge @ 2.421 nm
- calculated, ideal reflectivity (no roughness):



- 20 $\%_{abs}$ reflectivity loss with only 10 pm wavelength shift
- no flexibility in wavelength choice! (**needs to be very close to absorption edge!!**)

11 I 2025 EUVL and Source Workshop, Boston, 26-JUN-2025

optiX fab.

Torsten Feigl, 2025 EUVL and Source Workshop, June 25, 2025, MIT LL

Blue -X

EUV Litho, Inc.

3.1 WW ML Interfacial Roughness Needs to Be < 0.1 nm!

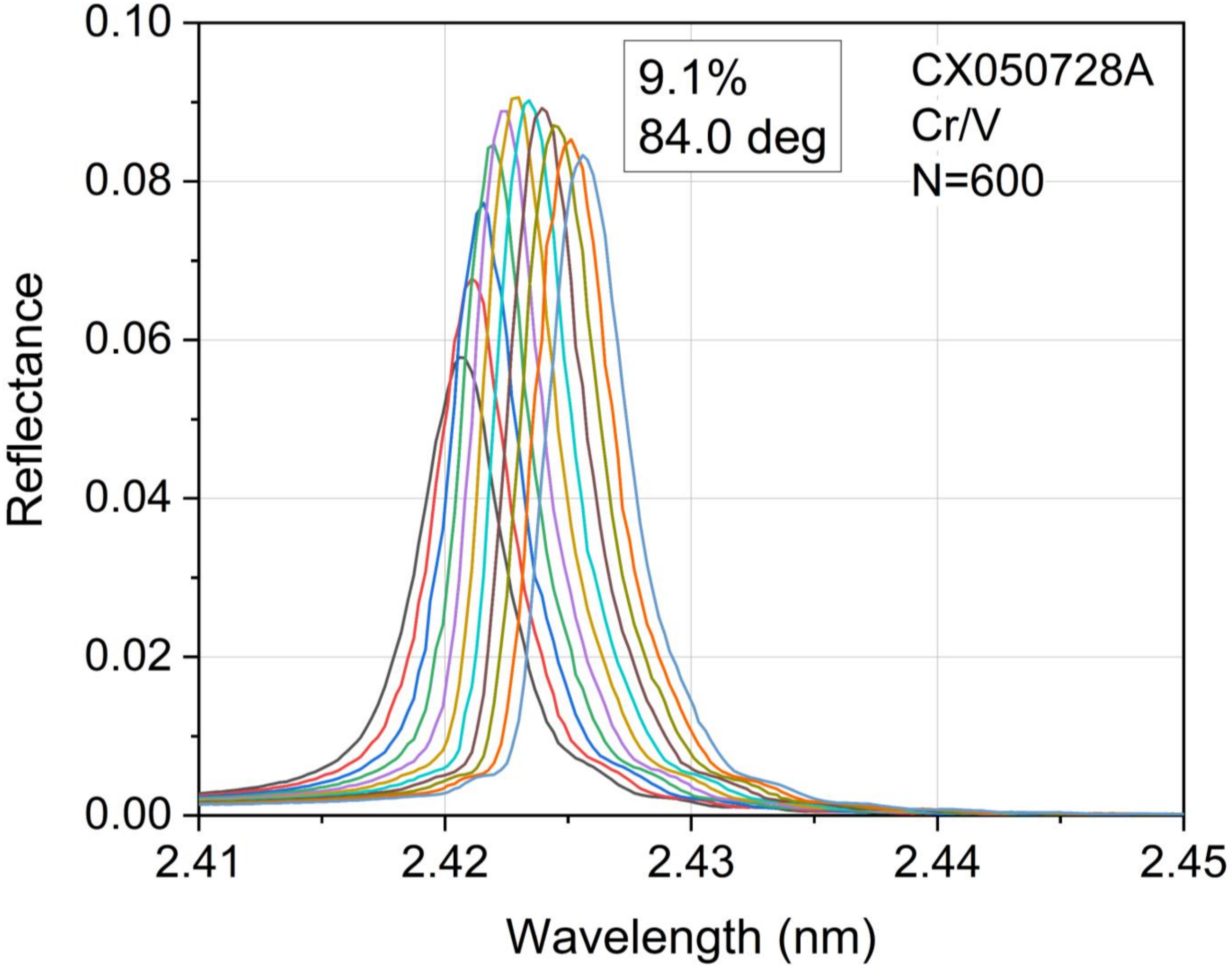
- **We have recent results showing this may be possible**:
  - High-power impulse magnetron sputtering (HiPIMS), compared to standard magnetron sputtering, in W/SiC MLs reduced interfacial roughness by a factor of two, from ∼0.4 nm to ∼0.2 nm.
    - This results in a significant increase in peak reflectivity, from 63% up to 79% at 40 keV, and in a broader bandwidth.


Optics Letters
HiPIMS deposition method unlocks higher X-ray reflectance in ultra-short-period multilayer mirrors
Corentin Nannini,[1] Nolann Ravinet,[1] Evgueni Meltchakov,[1] Christian Gollwitzer,[2] Thu Nhi Tran Caliste,[3] Antoine Lejars,[4] and Franck Delmotte[1,*]
[1] Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91120, Palaiseau, France
[2] Physikalisch-Technische Bundesanstalt, 10587 Berlin, Germany
[3] European Synchrotron Radiation Facility (ESRF), 71 avenue des Martyrs, 38000 Grenoble, France
[4] CEA, Centre DAM Ile-de-France, 91197 Arpajon, France
*franck.delmotte@institutoptique.fr
Received 27 June 2025; revised 12 September 2025; accepted 20 September 2025; posted 22 September 2025; published 21 October 2025

- **Three groups are very active in reducing interfacial roughness of ML mirrors in the WW ML**
  - University of Twente
  - Université Paris-Saclay
  - K-Program in Japan

3.1 ML Optics in WW: Cr / V Multilayers @ 2.4 nm

Peak @ 6%AOI ~ 2.425 nm, BW ~ 5 PMM / 0.2 %



- Projects in progress at CXRO to identify peak shift via use of VOx/Cr and VOx /CrN vs V/Cr

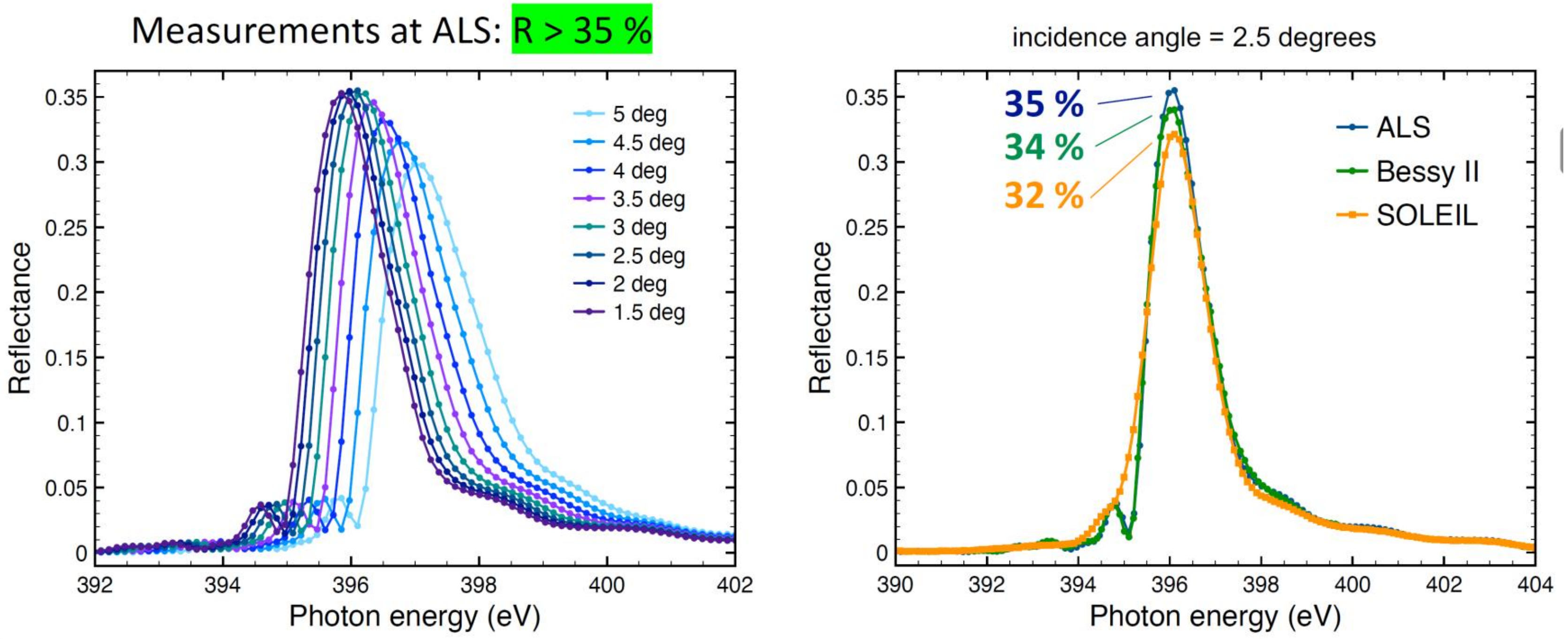
Source: Eric Gullikson, CXRO Private Communication

3.1 ML Optics in WW: Sc / Cr @ 3.1 nm (Current Choice)

3.127 nm / 396.5 eV: Peak @ 1.5% AOI 396 eV, @5% AOI 397 eV

Reflectance measurements on 3 different beamlines

[CrN/B_4C/Sc]x500, period d = 1.57 nm



7

F. Delmotte, EUVL workshop, 06/24/2025

Source: Franck Delmotte, 2025 EUVL Workshop

3.1 WW ML Choices

ML Pair	λ (Peak Reflectivity)	Notes	
Cr / V	2.4 nm	2.425 nm	Narrow BW
Cr / Ti	2.8 nm		
Cr / Sc	3.1 nm	3.127 nm/396.5 eV	Current Choice
Cr/K	4.2 nm		Need Halides
Cr / C	4.4 nm		Carbon

- Initial choice of 3.127 nm Sc /Cr ML to start our learning process
  - ~Middle choice, with active ML research program and public information
- **Depending on ML and plasma source availability, this choice many change**
- **We are providing a "wavelength band" around these peak reflectivity values to plasma source groups, to help identify potential candidates**

3.1 ML Bandwidth and Angular Bandwidth: Match with Plasma sources and FEL

- **ML Bandwidth are narrow, but this is not an issue, as sources are also narrow BW!**
  - ML BW are ~ 0.5% or less
  - Sc/Cr at 3.1 nm ~ (0.4% / 12 pm) ; V/Cr:2.4 nm (0.2% / 5 pm)
- Theoretical calculations show that BW of Plasma Emissions of choice in WW are narrow <1 pm – 10 pm
  - **FEL BW is 1% and can be scaled down (SASE) to 0.1%**
  - **Please note that @ 13.5 nm Source BW is 10% and Si/Mo BW ~ 4%**
- **Angular Bandwidth: Peak reflectivity drops for 3.1 nm ML is ~ 15 % in ~ 5 degrees (0.3 nm interfacial roughness). However, this will drop will reduce as interfacial roughness approach 0.1 nm and less**
- Wavelength for peak reflectivity shifts ~ 0.5% (~ 10 pm) from 0 – 6 degrees. This may be addressed via lateral grading of ML deposition

3.2 Challenges in Plasma Source Selection

- ML BW are narrow ~ 10s pm and so are the plasma lines in WW!
- Peak wavelength of plasma emission line needs to be within ~ few 10s pm of ML peak reflectivity
- ML reflectivity (peak, BW) depends on material choice, d spacing, angle of incidence, etc.
  - Most information from commercial suppliers is not public
  - However, some ML information is public
- **We need with "pm" precision information on: absorption edges location (some availability) and plasma source emission profiles (not available yet)**

3.2 ML Location: Absorption K and L_3 edges: C, K, Ca, Sc, Ti, V, Cr

		NIST	NIST(err)	IXAS	Booklet	Z1	Z2			λ (NIST)	λ(err)
		eV	eV	eV	eV	eV	eV			nm	nm
C				284	284.2					4.3626	
K		294.55	0.22	295	294.6	293.6	294.5			4.2093	0.0031
Ca		346.611	0.066	346	346.2	346.4	349.34			3.5770	0.0007
Sc		398.55	0.47	399	398.7	402.2				3.1109	0.0037
Ti		453.979	0.061	454	453.8	455.5	454.31			2.7311	0.0004
V		512.21	0.22	512	512.1	512.9				2.4206	0.0010
Cr		574.36	0.13	574	574.1	574.5	598.9			2.1586	0.0005

1. NIST: R.D. Deslattes, E.G. Kessler, Jr., P. Indelicato, L. de Billy, E. Lindroth, and J. Anton, "X-ray transition energies: new approach to a comprehensive evaluation," Rev. Mod. Phys. **75**, 35-99 (**2003**).
2. IXAS: https://xrayabsorption.org/xraytable/ (**2002**)
3. X-Ray Booklet: https://xdb.lbl.gov/ (**2009**)
4. Z1,Z2: G. Zschornack, Handbook of X-Ray Data (**2007**)

Blue -X

making circuit elements smaller!

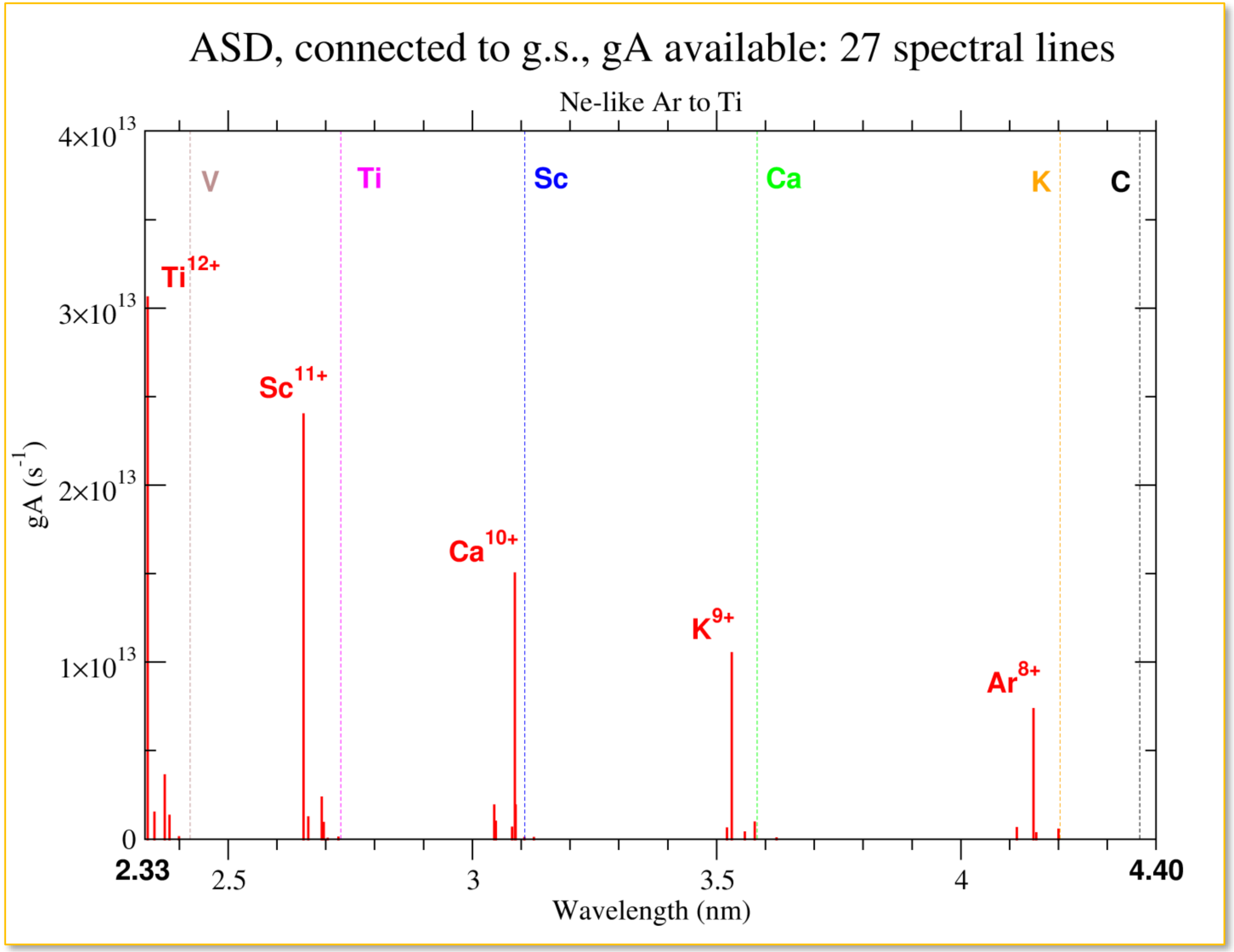
Courtesy: Yu. Ralchenko, 12/04/2025

EUV Litho, Inc.

3.2 Plasma Line Emissions: Ne-like Ions: Ar to Ti

- **Ne-like ions are the most abundant over large ranges of temperatures (closed shell $1s^2 2s^2 2p^6$)**
- **Required temperatures on the order of 30-80 eV**
- Plasma population kinetics is relatively simpler than in open-shell ions
- **Their lines are well separated and strong**
    - **Resonance lines $2p^6 - 2p^5 3d$**
    - ***Primarily within the water window***
- ASD: 45 lines from Ne-like ions within WW – now extended to several hundred lines
- **There are about 250+ spectral lines in ASD within ±10 pm from the absorption edges of the relevant elements**
- **About 10 of them *may* be useful for BEUV purposes**
- However, only a detailed modeling followed by accurate measurements may prove their usability

3.2 Plasma Lines in WW Region (First Estimate)



Yu. Ralchenko, 9/11/2025

Blue -X

EUV Litho, Inc.

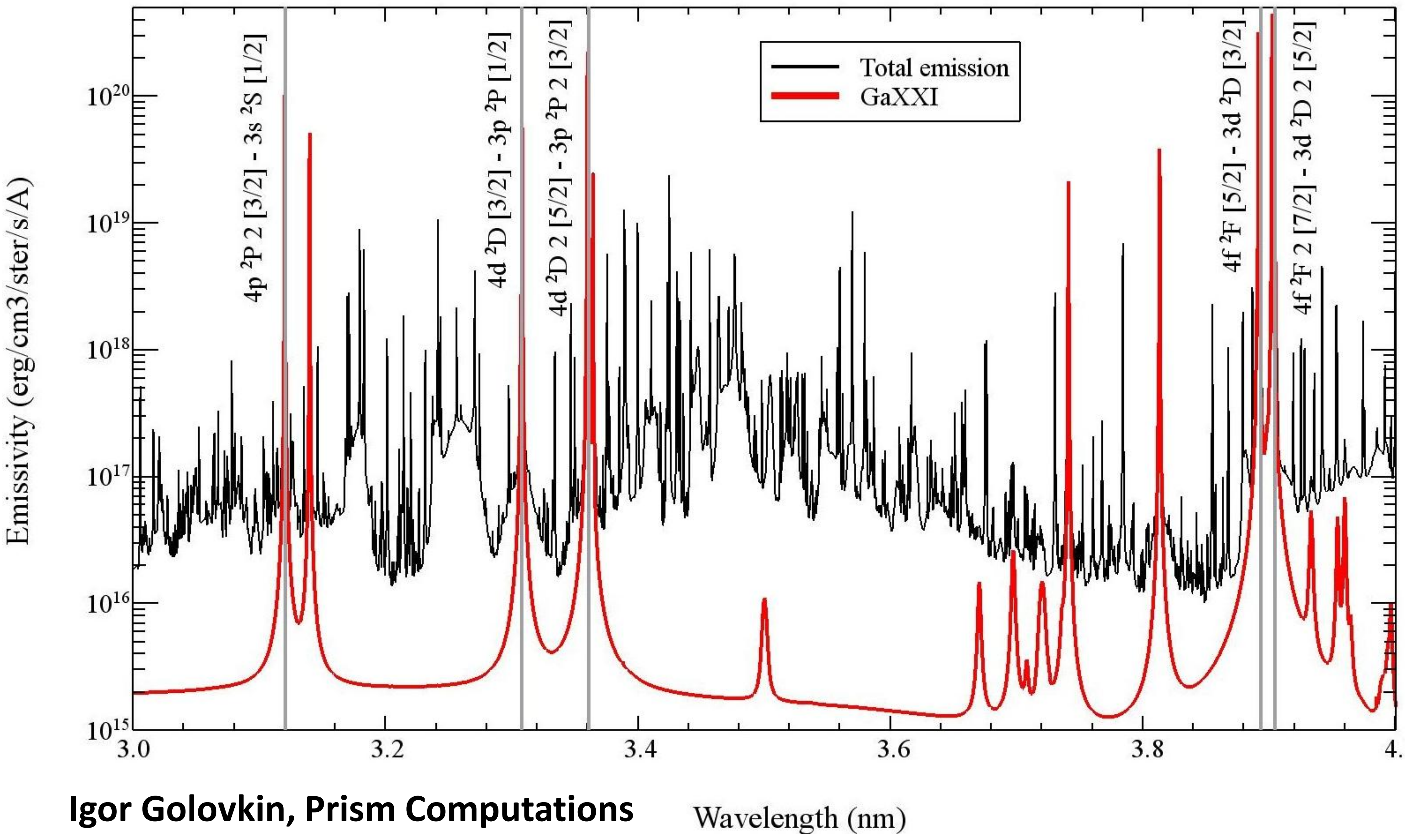
3.2 Plasma Source Evaluation: Recommended Lines for WW: Ga and Sc Selected for Initial Experimental and Theoretical Studies

element	sp_num	obs_wl_vac(nm)	unc_obs_wl	ritz_wl_vac(nm)	Aki(s^-1)	Ei(eV)	Ek(eV)	conf_i	term_i	J_i	conf_k	term_k	J_k		IP(eV)
			Carbon K	4.3626											
Ga	21	4.3683		4.3681		113.4934	397.33	2p6.3d	2D	5/2	2p6.4p	2P*	3/2		807.308
Si	11			4.37629	6.24e+11	0.0000	283.309	1s2.2s2	1S	0	1s2.2s.3p	1P*	1		476.273
			K L_3	4.2093											
Ar	9	4.2001	0.0002	4.19999		0.000	295.20117	2s2.2p6	1S	0	2s2.2p5.3d	3D*	1		422.6
			Ca L_3	3.5770											
S	13	3.5667		3.5667	1.66e+12	48.3021	395.92	1s2.2s.2p	1P*	1	1s2.2s.3d	1D	2		651.96
K	10	3.5779	0.0004	3.5781	3.13e+11	0.000	346.5098	2s2.2p6	1S	0	2s2.2p5.(2P*<3/2>).3d	2[3/2]*	1		503.67
			Sc L_3	3.1109											
Ga	21	3.1203		3.1204		0.0000	397.33	2p6.3s	2S	1/2	2p6.4p	2P*	3/2		807.308
			Ti L_3	2.7311											
Sc	12	2.7260		2.725876	2.4e+10	0.0000	454.8417	2s2.2p6	1S	0	2s2.2p5.(2P*<3/2>).3d	2[1/2]*	1		687.36
			Ca L_2	3.5384											
K	10	3.5307	0.0004	3.5309	3.51e+12	0.000	351.1378	2s2.2p6	1S	0	2s2.2p5.(2P*<1/2>).3d	2[3/2]*	1		503.67
			Ti L_2	2.6953											
Sc	12	2.6920		2.6920	7.800e+11	0.0000	460.56	2s2.2p6	1S	0	2s2.2p5.(2P*<3/2>).3d	2[3/2]*	1		687.36
			V L_2	2.3856											
K	16	2.384	0.0010	2.3842	4.3e+12	60.108	580.12	2s.2p	1P*	1	2s.3d	1D	2		967.7

Yu. Ralchenko, 12/04/2025

All lines: **https://tinyurl.com/cvcw6t7e**

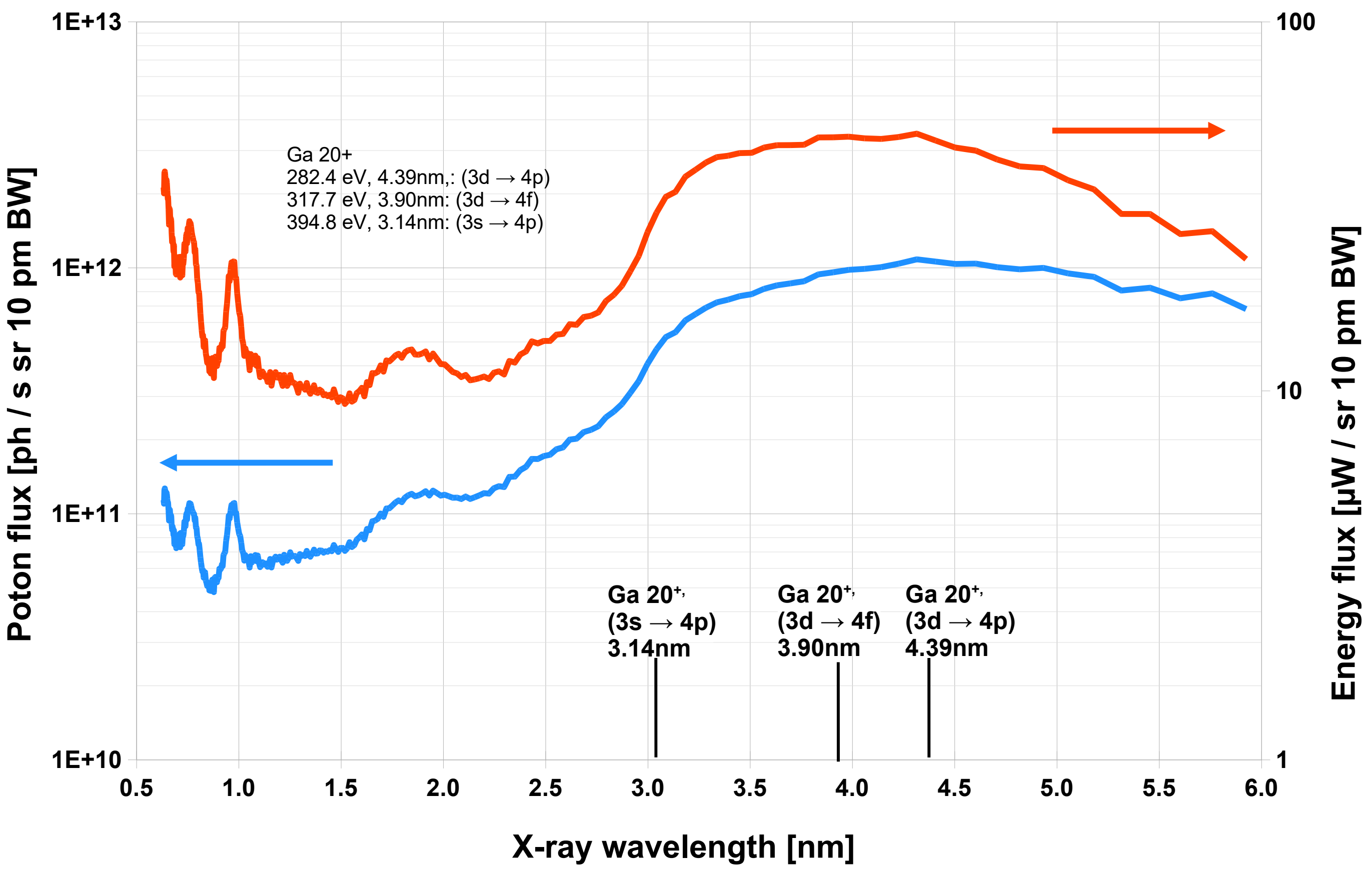
3.2 Ga Plasma in WW (Simulation)



Igor Golovkin, Prism Computations

3.2 Plasma Sources in Water Window (Ga)

Research Instruments Corporation (RIC)
Absolutely calibrated emission from Ga-target Laser plasma X-ray source (LPXS)



Laser:
4mJ/pulse, 20kHz, 150ps, 1030nm

Target:
Liquid Ga
Flat jet
Laser beam incidence angle: 45°

Detecor:
Amptek SDD-C1
130eV resolution

Predicted flux at 3.14 eV with production laser:
3×10^{12} ph/s sr

Learn more

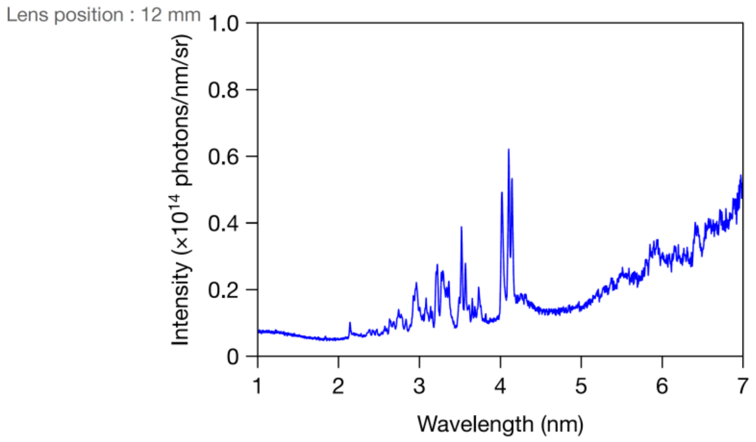
Contact Dan DeCiccio, CEO,
ddeciccio@resinstcorp.com,
Tel. 407.619.8694
Web: resinstcorp.com

RIC presents this week at SPIE

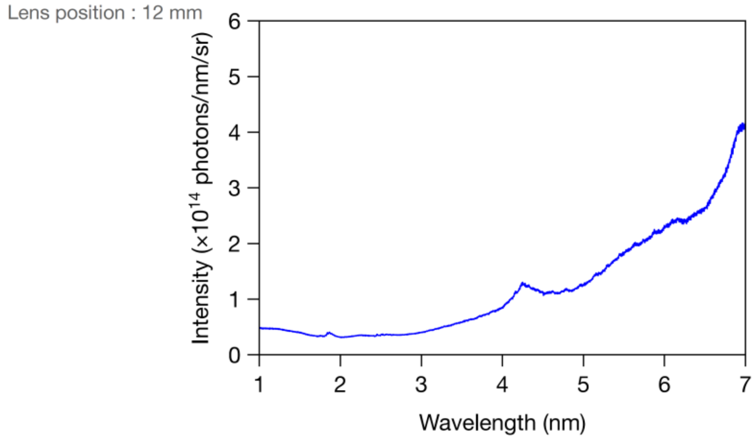
3.2 Plasma Sources in 6.7 nm and WW Region

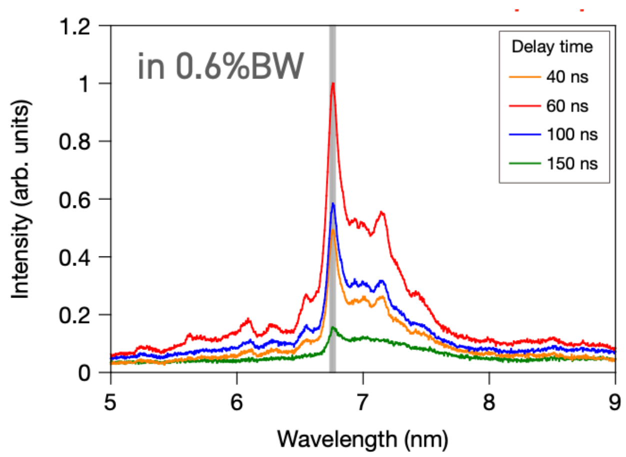
(Ref: Takeshi Higashiguchi, Utsunomiya)

Spectrum from K plasma

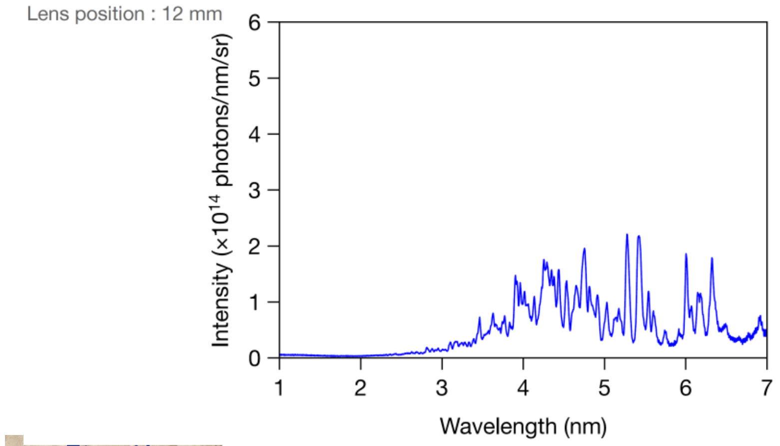


Spectrum from Sn plasma

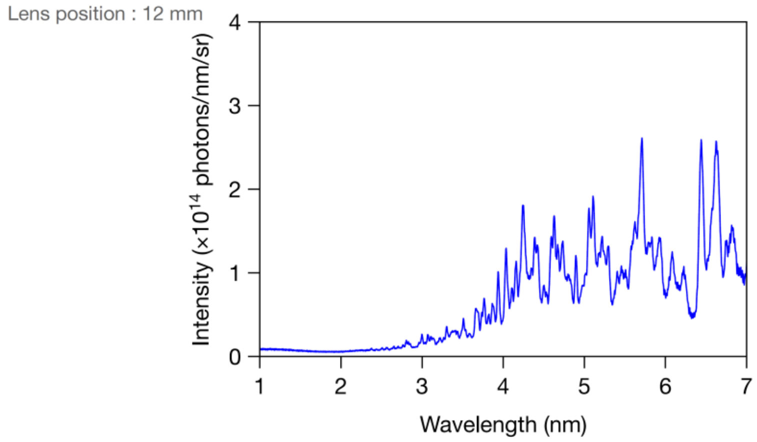




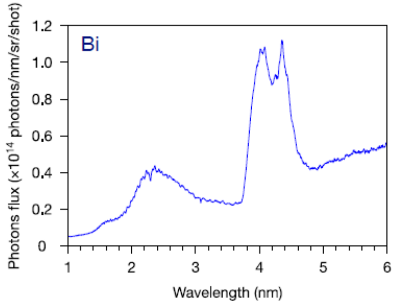
Spectrum from S plasma



Spectrum from P plasma



- Candidate targets for UTA emission in WW-SXR
  →Bi, Au, Mo, etc.

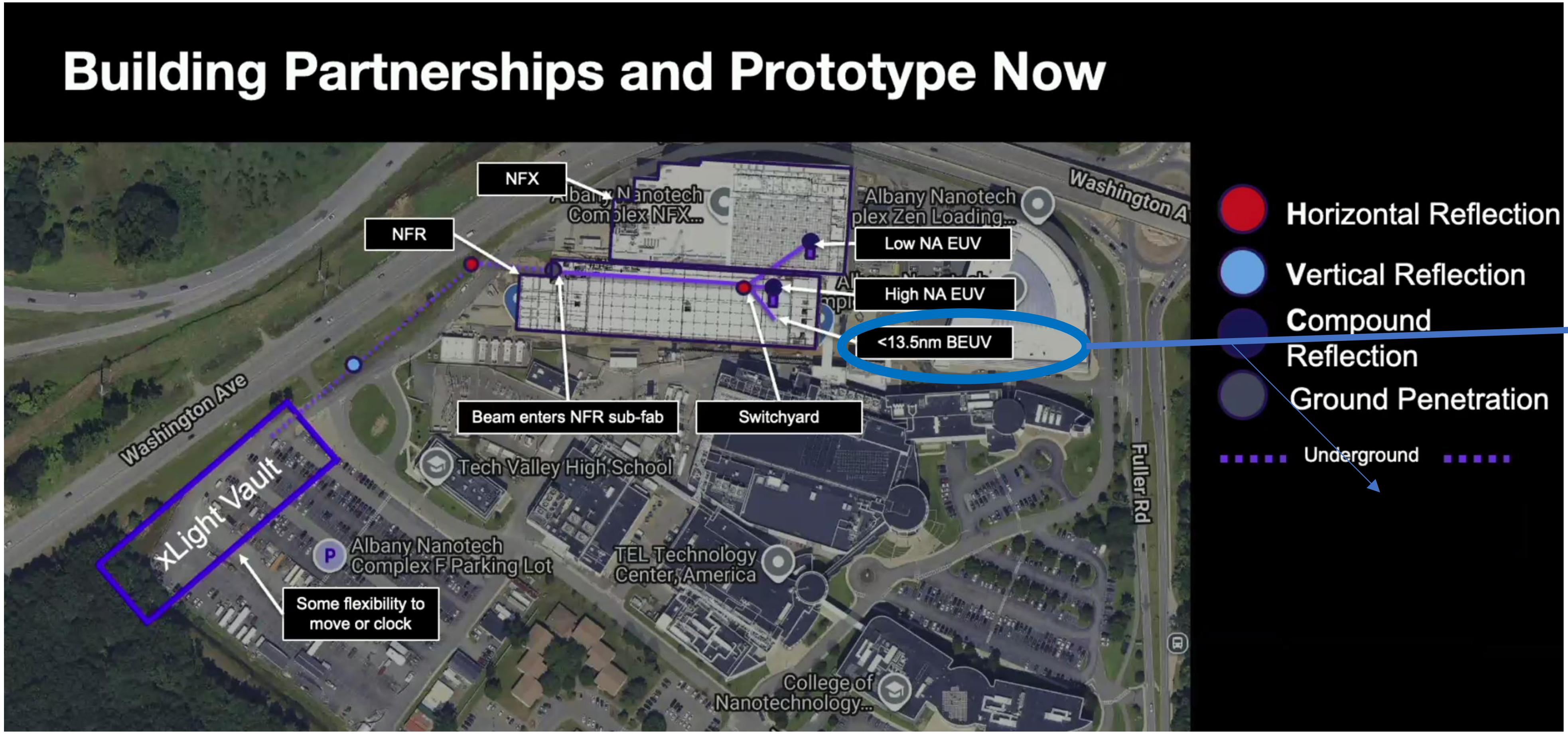


Bi has a low melting point (272°C)

3.2 Non-Plasma Sources: FEL

- Potential to generate **1-10 kW** at 13.5 nm and at shorter wavelengths
- **Can offer tunable wavelength in 2-7 nm**
- **No OoB radiation**
- **BW ~ 1%** (Compared to 10% BW for Sn LPP) and SASE FEL can be tuned down to 0.1%, allowing flexibility
- xLight recently received substantial funding to build a prototype – short wavelength (Blue-X) line planned at Albany
- Expect first light 2028

3.2 xLight's Planned FEL Prototype has <13.5 nm Option



Blue-X Beamline

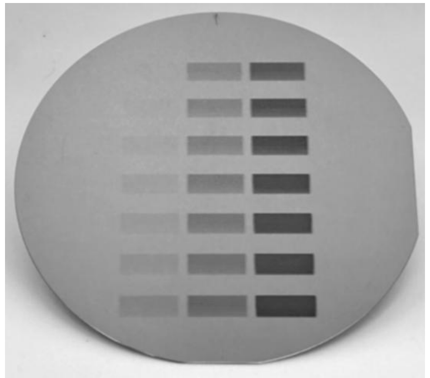
Ref: Nicholas Kelez, xLight, 10th FEL Workshop, January 2026

3.3 Blue-X Resist Studies Efforts at Berkeley Lab:

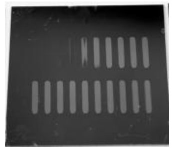
Resist Evaluation at 6.7 nm and 3.1 nm

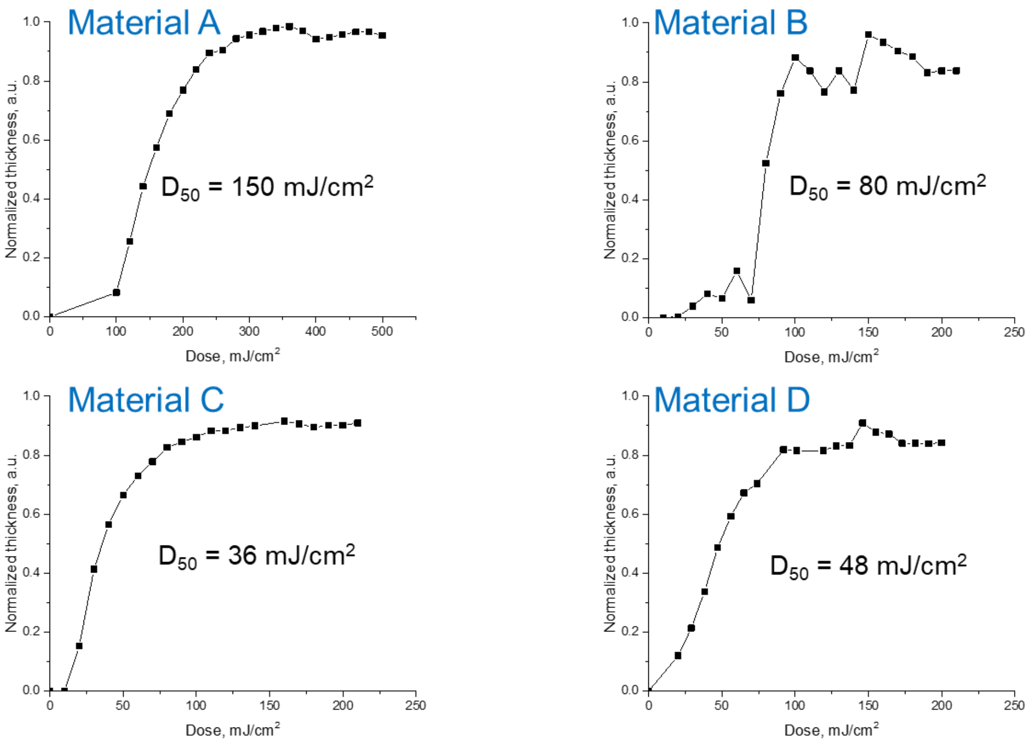
Developed different blanket exposure modes at 6.7 nm

Large spots



Small spots





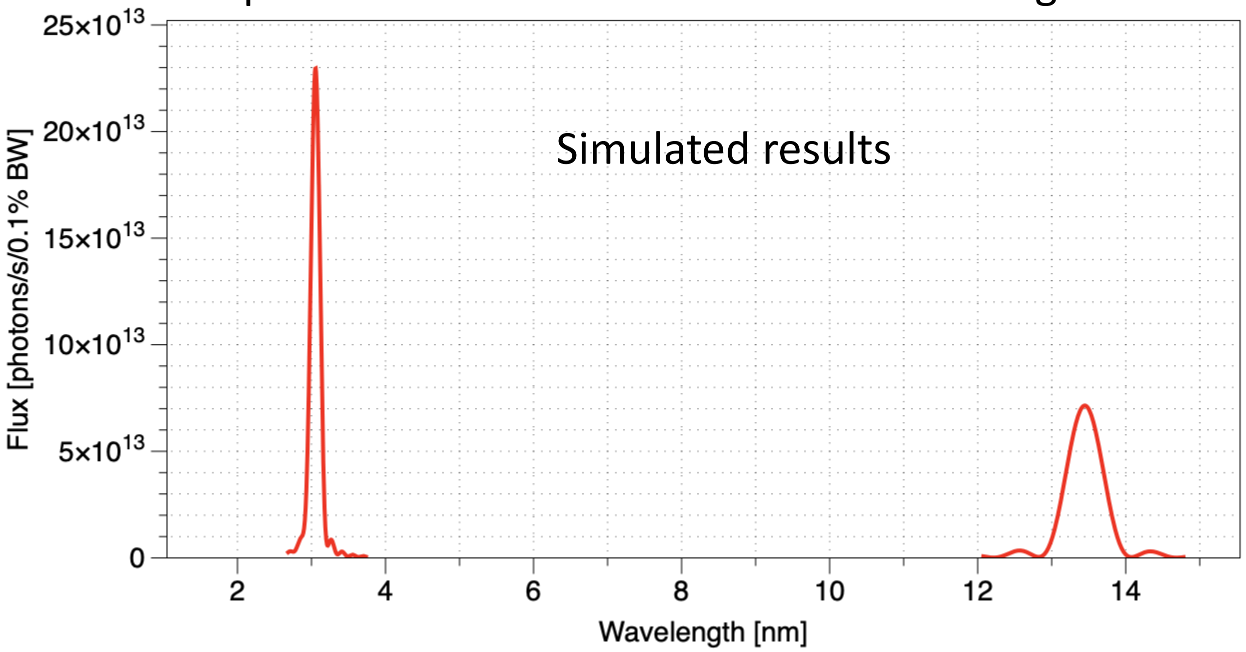
- Performed dose calibration measurements on **17 samples** from industry, universities, and national labs. From them 10 negative tone and 7 positive tone resists.
- **Observed D_{50} measurements in the 50–150 mJ/cm² range**
  - With one low outlier below 2 mJ/cm² and one high outlier above 2000 mJ/cm².
  - Two publications by Michael Tsapatsis et al. and collaborators

- **Performed preliminary tests at 3.1 nm. Achieved 2x improvement in flux at 3.1 nm since December.**

Credit: Oleg Kostko (CXRO), Resist sub –TWG Co-chairs and members for contributing resist for studies

3.3 Blue-X Patterning and Resist Evaluation at PSI:
Resist Evaluation and IL @ 3.1 nm

The first light at the new XIL-II beamline is scheduled for June 2026. Open-frame exposures and IL exposures will be scheduled in the following months.



- The EUV flux will be comparable to the previous XIL-II values.
- At 3.1 nm, the flux will be more monochromatic and approximately twice as high.

Wavelength	Peak Flux	Integrated flux
3.1 nm	23×10^{13} photons/s/0.1% BW	7×10^{15} photons/s
13.5 nm	7×10^{13} photons/s/0.1% BW	3×10^{15} photons/s

- Resists will be evaluated @ 3.1 nm at Berkeley lab until July, before planned shutdown
- Resists will be further evaluated at PSI at 3.1 nm, from July, before IL experiments with selected resists

3.4 Blue-X Optics Requirements:

MSFR and Dose Uniformity Implications for Blue-X @ 3.1 nm

1.Flare: To keep the flare at 4 % need to shrink the net rms of the σ_{MSFR} of the projection optics mirrors by the same amount that the wavelength shrinks. Current EUV optics specs are <80 pm. However, as the data stops in past, state of the art is probably better.

$\lambda = 13.5$ nm → $\lambda = 6.7$ nm ➔ $\sigma_{MSFR} = 80$ pm → $\sigma_{MSFR} \cong 40$ pm to keep 4 % flare

$\boldsymbol{\lambda = 13.5}$ nm → $\boldsymbol{\lambda = 3.1}$ nm ➔ $\boldsymbol{\sigma_{MSFR} = 80}$ pm → $\boldsymbol{\sigma_{MSFR} \cong 20}$ pm to keep 4 % flare

Assume six mirrors:

2. Dose Uniformity (Speckle Averaging Contribution)

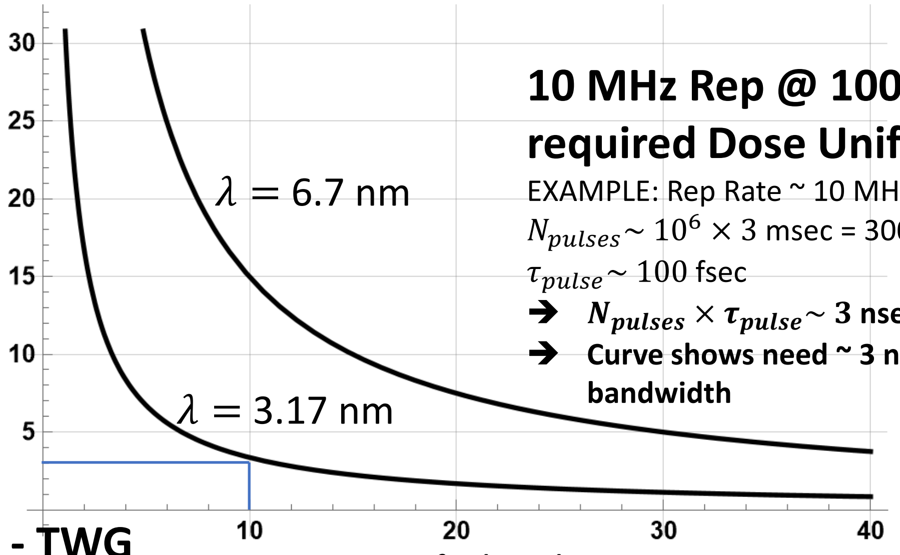
$$c\frac{\Delta\lambda}{\lambda^2} \times N_{pulses} \times \tau_{pulse} > 10^6 \quad ➔ \quad N_{pulses} \times \tau_{pulse}$$

(nsec)

$$N_{pulses} \sim \underbrace{3\,msec}_{} \times Pulse\ Rep\ Rate$$

3 mm wide slit @ 1 m/s scan speed

Minimum "allowed" value of $N_{pulses} \times \tau_{pulse}$



10 MHz Rep @ 100 fs will allow required Dose Uniformity

EXAMPLE: Rep Rate ~ 10 MHz

$N_{pulses} \sim 10^6 \times 3$ msec = 3000

$\tau_{pulse} \sim 100$ fsec

➔ **$N_{pulses} \times \tau_{pulse} \sim 3$ nsec**

➔ **Curve shows need ~ 3 nsec at 10 pm bandwidth**

Gregg Gallatin, Applied Math, Co-chair, Optical Design Sub - TWG

3.5 Mask sub-TWG: Draft Specs and Subgroups

- **Strong Mask industry participation**
- **Validate baseline requirements and work with optical and ML group to define spec. for Blue-X mask**
- Owner/Co-owner to work together for each requirement for the following subgroups:
  - Substrate/Backside Coating – Roni & Uno-san
  - Multilayer/Cap – Ben & Benny
  - Absorber – Markus & Mochi, Sakurai-san is considering
  - Mask – Jed
- Photomask suppliers to present their vision and capability for Blue-X (Next Meeting)

Substrate Properties

Reticle Design Requirements	Current (Baseline)	Technology	Blue-X	Technology	Lead
Substrate Properties					
Substrate material	LTEM				
Edge width	152 ± 0.1				
Edge length	152 ± 0.1				
Squareness	0.01/25.4				
Thickness	6.35 ± 0.1				
Notch dimensions	4 ± 1				
Notch depth	0.75 ± 0.5				
Mean CTE	0 ± 5				
CTE spatial variation range					
Dimensions flatness quality ar					
TIR front side					
TIR backside					
Wedge angle					
Front side Quality Area (QA)					
Front flatness in QA (13nm hp)					
Back side Quality Area (QA)					
Back flatness in QA (13nm hp)					
Bow (13nm hp) - over 142mm x					

Multilayer/Cap Properties

Reticle Design Requirements	Current (Baseline)	Technology	Blue-X	Technlogy	Lead
Multilayer/Cap Properties					
Quality Area - Zone 1	≤ 132 mm x 132 mm (centered on the reticle), ± 0.1 mm	Ion Beam Deposition			
Quality Area - Zone 2	> 132 mm x 132 mm, ≤ 140.4 mm x 140.4 mm (centered on the reticle), ± 0.1 mm	Physical Vapor Deposition EUV Reflectometer			
Quality Area - Zone 3 - no performance requirement	> 140.4 mm x 140.4 mm (centered on the reticle), ± 0.1 mm	XRR			
Quality area corner rounding radius	≤ 14 mm	XRF			
ML material	Mo/Si	Ellipsometer			
Pairs of Multilayer (n=?)	40 or 50	AFM			
Centroid Wavelength (CW)	13.53± 0.0135/13.5± 0.0203	Actinic Blanks Inspection			
Max. range of CW - Zone 1	≤0.04/≤0.02	Particle Inspection			
Max. range of CW - Zone 2	≤0.1	Annealing			
Dimensions defect inspection area		Cleaning			
Demensions defect quality area					
Defectivity					
beyond Actiniv Inpsection bABI: count? @ ? Nm SEVD					
Peak reflectivity - Zone 1	≥ 67				
Peak reflectivity uniformity - Zone 1	≤ 0.3				
Peak reflectivity - Zone 2	≥ 60				
Peak reflectivity uniformity - Zone 2	≤ 1				
Cap layer mat					
Cap layer thick					

Absorber Properties

Reticle Design Requirements	Current (Baseline)	Technology	Blue-X	Technlogy	Lead
Absober Properties					
Absober material	TaBN	Physical Vapor Deposition			
Absorber thickness	40 < h < 100	EUV Reflectometer			
Stack height variation across the blank	± 1% of h	XRR			
Absorber thickness uniformity		XRF			
Defectivity		Ellipsometer			
Reflectivity averaged over the wavelength range 13.395 - 13.665 nm		AFM			
		Particle Inspection (?) Cleaning			

Backside Coating Properties

Reticle Design Requirements	Current (Baseline)	Technology	Blue-X	Technlogy	Lead
Backside Coating Properties					
Backside coating material	CrN and TaB	Physical Vapor Deposition			
Quality area	146x146	Ellipsometer			
Backside coating area	≥ 148x148	Particle Inspection (?)			
Backside coating thickness (min)	20				
Thickness range	≤ 2%				
Sheet resistance	<100				
Optical density @ 470nm	>2.0				
Surface roughness	≤ 0.6 nm rms (≤ 10 µm spatial wavelength)				
Defectivity					
Backside bow (TIR of full stack blank)					
Sheet resistance					

Courtesy: Meng Lee (Veeco) and Ben Eynon (LAM)

3.6 Blue-X Lithography: Paths to “Lower Stochastics”

- 3.6.1 3-beam Lithography
- 3.6.2 Dose Partitioning
- 3.6.3 Larger Mask (12 inch masks for 8X)
- 3.6.4 Image Contrast Improvement via “ Soft-Xray Microscopy” Techniques (this will need well established baseline patterning process)

3.6.1 3-beam Imaging Enables Reduction in LER

A: Stochastics

$$LER \propto \frac{1}{\sqrt{N}} \times \frac{1}{ILS}$$

Our mission: Reduce Stochastic induced variation (LER) while enabling single expose <16nm pitch solution

Proposed path: Increase ILS faster than $\sqrt{N}$ decreases with resists that are not limiting

A: Stochastics

$$LER_{3.1nm} \sim \frac{2}{2.5} LER_{13.5nm}$$

Mission: Reduce Stochastic induced variation (LER) while enabling single expose <16nm pitch solution

Mission accomplished

ILS for different mask materials and biases

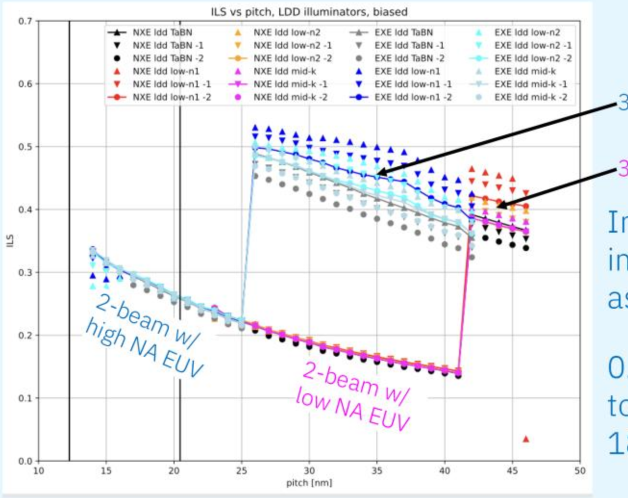


Image log slope for 3-beam imaging ~2.5 times as high as 2-beam imaging

0.75 NA EUV has a 3-beam to 2-beam transition at 18nm pitch

- **Potential for 20% reduction in LER**
- Overall 2x increase due to photon wavelength
- 2.5 x increase from 3-beam imaging

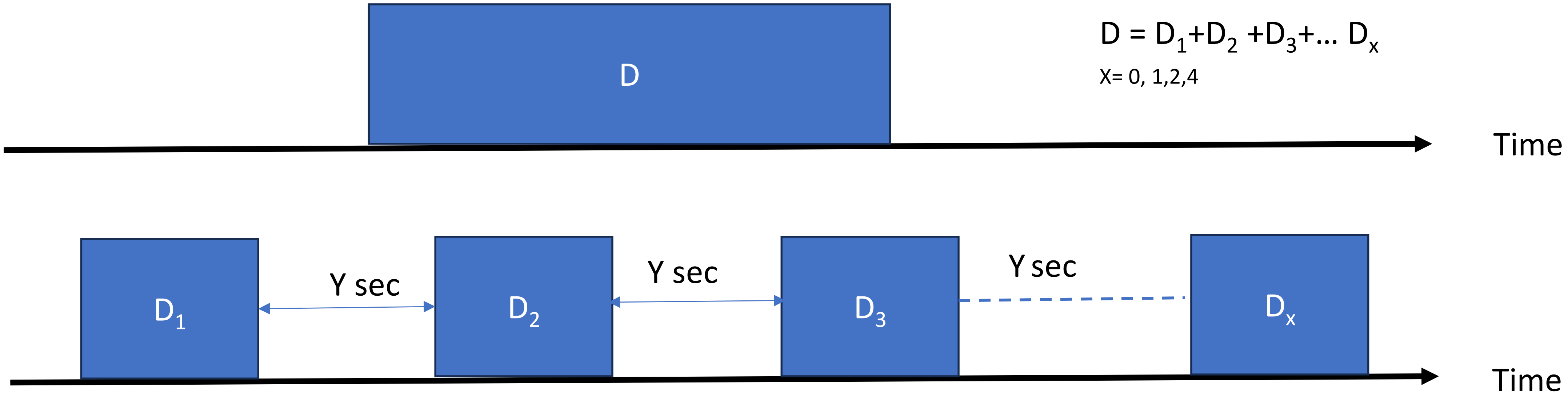
Courtesy: Allen Gabor, IBM (2025 EUVL and Source Workshop)

3.6.2 Hypothesis and Experimental Framework for Exposure Partitioning on MET: Is there potential to "average out" noise through time-domain partitioning?

- **While total photon counts remain constant, the Non-Photon contributors to stochastics and the Resist Chemistry dynamics provide several favorable mechanisms:**
  - Averaging Systematic Roughness
  - Averaging Resist & Material Inhomogeneity
- **It moves us from a "brute force" dose approach to a "smart timing" approach.**
- If this experiment shows even a 5-10% reduction in LER, it changes the roadmap for both LPP and FEL-based source requirements.
  - There will be several way to accomplish this dose partitioning on LPP and FEL sources

3.6.2 Hypothesis and Experimental Framework for Exposure Partitioning on MET: Experimental Plan

- Proposal is to partition the dose D (mJ), for exposure of a given size (preferably best resolved) X nm L/S features, into 'x' parts, separated in time by 'y'
- At MET (13.5 nm using a MOR) , what are the best values for x and y?
- **Experiment in progress and will be repeated at 3.1 nm at PSI**



$D = D_1 + D_2 + D_3 + \ldots D_x$

X= 0, 1,2,4

3.6.3 300 mm (7 X) or 12” mask (8x) Enables Lower Mask 3D Effects and Lower MEEF

Why interest in 300mm mask format for short wavelength lithography?

Answer: increased magnification

- Reduced mask 3D effects:
  - Absorber aspect ratio
  - Reflection depth from multilayer
- Easier mask making for future nodes with more complex OPC solutions

IBM

Courtesy: Allen Gabor, IBM (2025 EUVL and Source Workshop)

4. Blue-X TWG Consortium:

Summary

EUV
LITHO, INC.

Blue -X
making circuit elements smaller!

4. Summary: Potential Throughput for a 3.1 nm Scanner:

As a Function of ML reflectivity, # of Reflections, Input Power

Parameter					
% TPT for 11 reflections @ 70% ML Reflectivity (13.5nm)	1.98	1.98	1.98	1.98	1.98
	Today	3-5 Yrs		10 Yrs	
ML Reflectivity (3.1 nm)→	**40%**	**45%**	**50%**	**55%**	**60%**
11 Reflections TPT (%)	0.00	0.02	0.05	0.14	0.36
(% of 13.5 nm TPT)	**0%**	**1%**	**2%**	**7%**	**18%**
9 Reflections TPT (%)	0.03	0.08	0.20	0.46	1.01
(% of 13.5 nm TPT)	**1%**	**4%**	**10%**	**23%**	**51%**
9 Reflections, 4 x Input Power TPT (%)	0.10	0.30	0.78	1.84	4.03
(% of 13.5 nm TPT)	**5%**	**15%**	**40%**	**93%**	**204%**

Assumptions:

- **Reduce 2 reflections at lower NA (0.26) and Higher k1 (0.6)**
- **4x input power to compensate for lower reflectivity**

Legends (% TPT of 13.5 nm)
Not feasible
MET Level (5%)
Alpha Level (10%)
Beta level (20%)
First Model (30%)
Production (50%)

4. Technical Feasibility of Lithography @ 3.1 nm

Technology Element	Values needed for HVM	Today	3-5 Years	~10 Year
Plasma Sources (WW)	kW Level	mW	10 W	kW level
Solid-state Lasers	100 kW Level (2 μ)	>5 kW (1μ)	~1 kW (2μ)	Under study
FEL	kW Level	mW	>10s W	~10 kW Level
Source Metrology	Flying Circus	Feasible	OK	OK
ML Reflectivity	~ 60%	~40%	~50%	~ 55-60%
ML Metrology	Measure ML performance	OK	OK	OK
Mask	Support 4-8 X patterning	Under study	Possible	Possible
Mask Metrology (SHARP)	Design for 7 nm HP	Under study	Possible	Possible
Optical roughness	20 pm	50 pm	<50 pm	10s of pm
Optical Metrology	20 pm	<50 pm	Possible	Possible
Resist Studies (Dose)	Needed	Possible	Possible	Possible
Resist Studies (Res. /LER)	Needed	Possible	Possible	Possible
Resist for 7 nm HP	7 nm HP Req.	TBD	TBD	TBD
Stochastics (LER)	7 nm HP Req.	TBD	TBD	TBD
Patterning Tool (IL)	Evaluate RLS	Feasible	OK	OK
		Design	Prototype	
Patterning Tool (MET)	Evaluate RLS	Feasible	Feasible	OK
			Design	
Patterning Tool (Scanner)	Design for 7 nm HP		Feasible	
Patterning Tool (Scanner)	7 nm HP tool			TBD

4. Critical Technologies to Enable Blue-X Lithography @ 3.1 nm: These are technology upgrades and NOT new technologies!

- Optics
  - Defect free ML deposition at atomic level, for near perfect interfaces, to enable 60% reflectivity for ML in the WW
  - ~ 20 pm optical roughness
- Source
  - For Plasma Sources: 100 kW class solid state lasers
  - FEL: 10 kW +FEL and associated infrastructure, energy efficiency
    - Compact FELs
- New Resists to address stochastics and resolution

4. Summary

- Blue-X TWG industry-wide consortium is exploring shorter wavelength lithography to extend Moore's Law
  - Initial experimental focus is now at 3.1 nm
  - ML: Understating ability to shift peak wavelength via experiments, measurements, and modeling
  - Sources: Identifying plasma sources at 3.127 nm. FEL development in progress
  - Resist: Resist evaluation in progress at 3.1 nm. Planned patterning via IL at PSI in July 2026
- "Blue-X MET" is a "possibility" in 3-5 years with continued efforts
- **This is an industry-wide effort so join us if you are not a member of the Blue-X TWG.**
- **Don't get left behind and write to us: Info@euvlitho.com for the Blue-X TWG White Paper**

Backup Slides