EUV OPTICS LIFE TIME RESEARCH, PAST, PRESENT AND FUTURE

Norbert Koster, Edwin te Sligte, Arnold Storm, Herman Bekman, Jacques van der Donck, Diederik Maas, Jochem Janssen, Rogier Verberk

TNO innovation for life

OUTLINE

- Past
- Present
- Future
- Conclusion

PAST

- The early years
- Carbon growth
- Clean vacuum
- DGL
- Mitigation (EToH/O_2)
- Cleaning with H*/H+

THE EARLY DAYS

Control of debris production of laser plasma sources with high average XUV power

F. Bijkerk, E. Louis, L. Shmaenok, H.J. Voorma, M.J. van der Wiel, I.C.E. Turcu*, G.J. Tallents*
FOM-Institute for Plasma Physics Rijnhuizen, Edisonbaan 14, 3439 MN Nieuwegein, The Netherlands,
*Rutherford Appleton Laboratory, Chilton, Didcot, UK

SPIE Vol. 1848 Laser-Induced Damage in Optical Materials: 1992 / 517

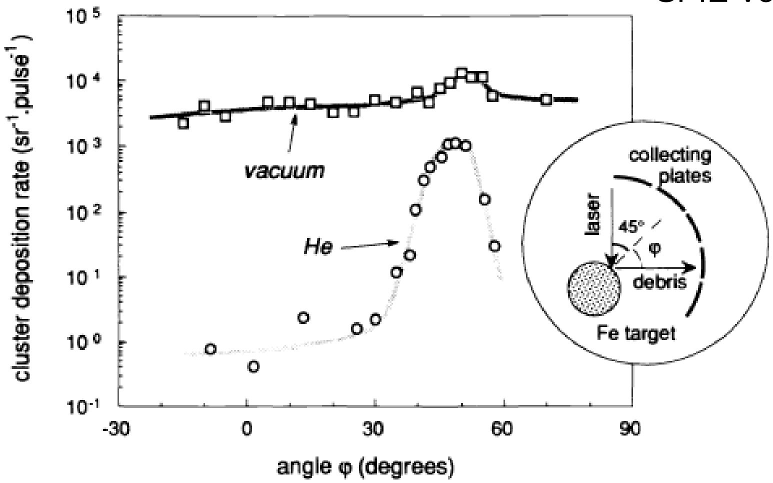
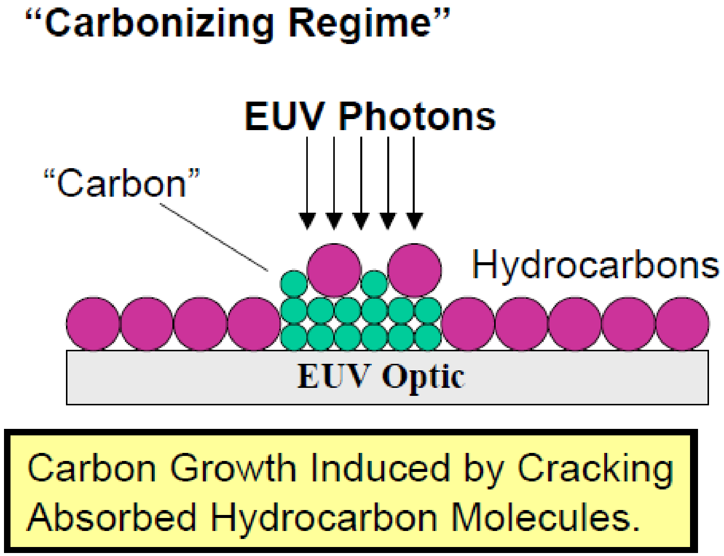


Fig. 1. Deposition rate of clusters in vacuum and in He at sub-atmospheric pressure. The inset shows the experimental set-up.

CARBON GROWTH

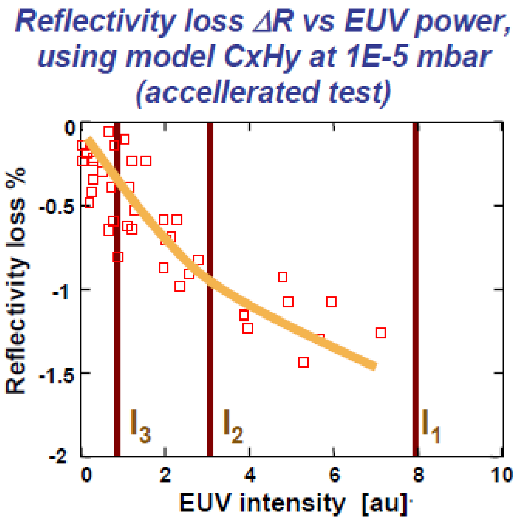
- Was one of the showstopper for EUV lithography
  - Sources:
    - Residual gasses from vacuum
    - Resist outgassing
    - Impurities in gas supply
    - Greases etc. from moving parts

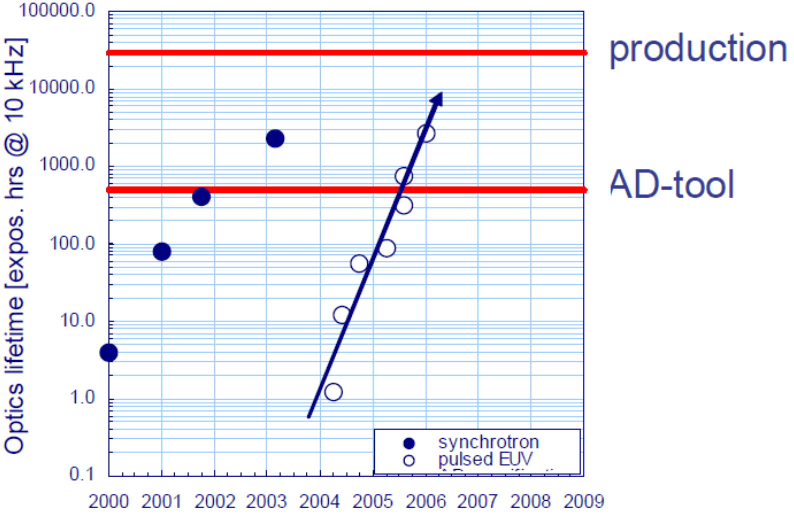


Graham *et al*, EUV contamination workshop 2003

CARBON GROWTH

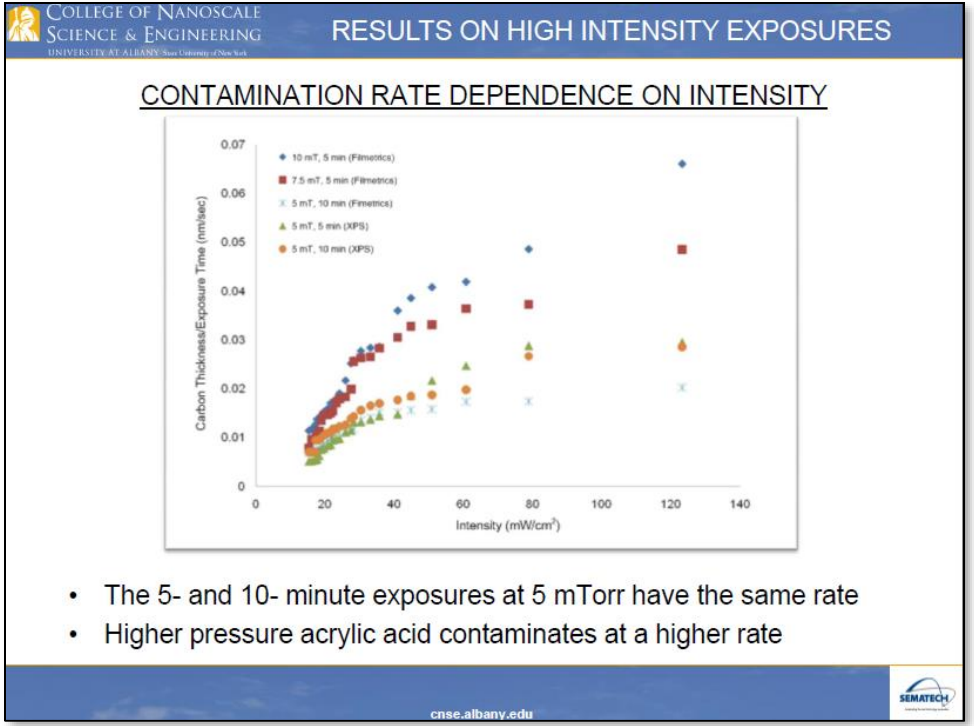
- Scales with partial pressure and type of hydrocarbon, EUV intensity and EUV pulse shape





H. Meiling *et al*, EUVL symposium 2006

CARBON GROWTH



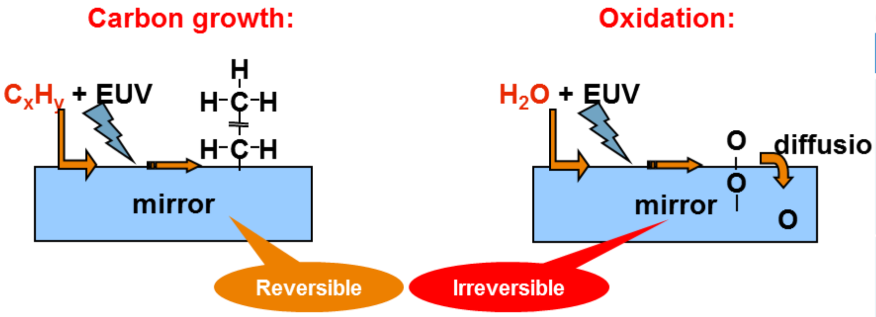
Thomas *et al*, EUVL symposium 2010

CARBON GROWTH

- Reducing carbon growth:
  - Minimize residual hydrocarbons (Ultra Clean vacuum, grease free design)
  - Protect sensitive surfaces
  - Mitigation (oxidation, reduction)
  - Cleaning

ULTRA CLEAN VACUUM (UCV)

- One of the problems: Carbon contamination of EUV mirrors



This happens at hydrocarbon pressures below 1E-12 mbar!

DIFFERENCE BETWEEN ULTRA HIGH VACUUM AND ULTRA CLEAN VACUUM

	UHV	UCV
Total pressure	Extremely low (e.g. < 10^{-9} mbar)	Moderate (e.g. < 10^{-1} mbar)
Specific components (e.g. hydrocarbons)	Extremely low (e.g. < 10^{-10} mbar)	Ultra low (e.g. < 10^{-12} mbar)

Koster *et al*, AVS annual symposium 2014

DGL

Mitigation of surface contamination from resist outgassing in EUV lithography

B.M. Mertens[a], B. van der Zwan[a], P.W.H. de Jager[a], M. Leenders[a], H.G.C. Werij[a], J.P.H. Benschop[b] and A.J.J. van Dijsseldonk[b]
[a]TNO Institute of Applied Physics, P.O. Box 155, 2600 AD Delft, The Netherlands
[b]ASML, De Run 1110, 5503 LA Veldhoven, The Netherlands

MNE proceedings 1999

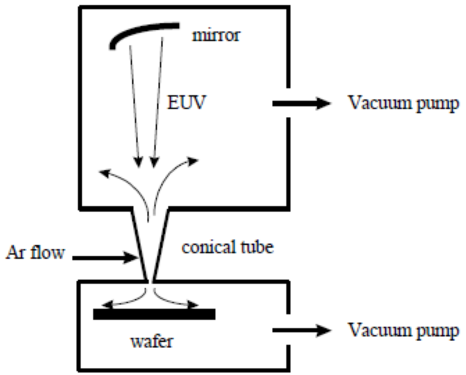


Figure 1. Principle of the dynamic gas lock system in an EUV tool.

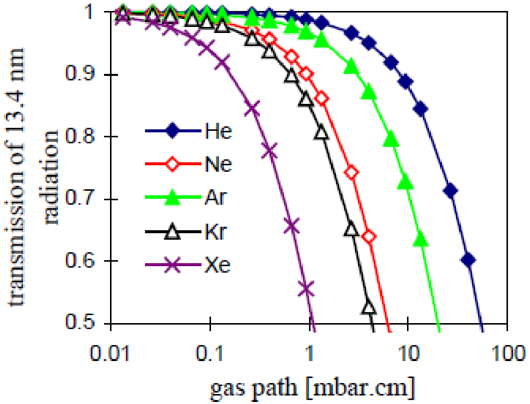
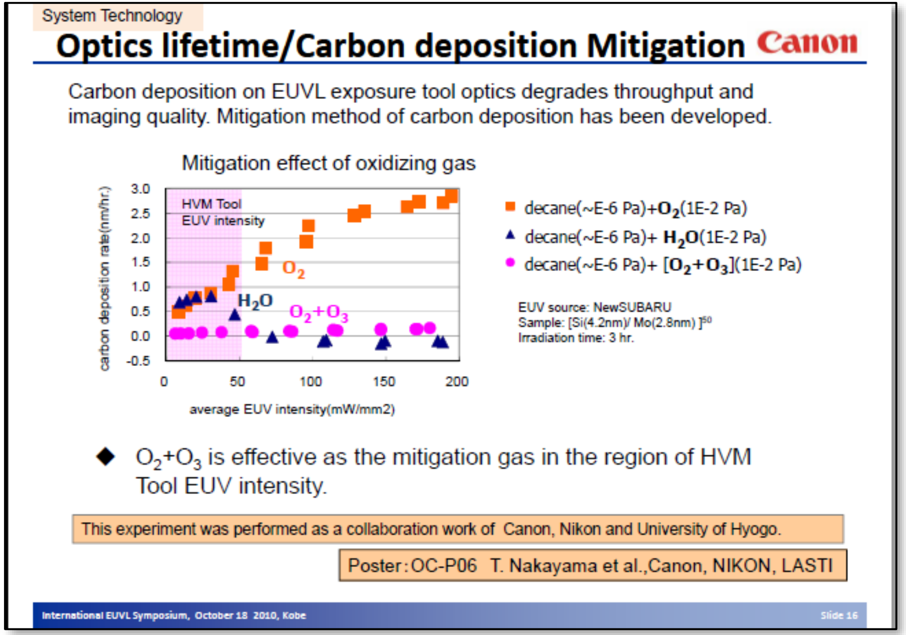


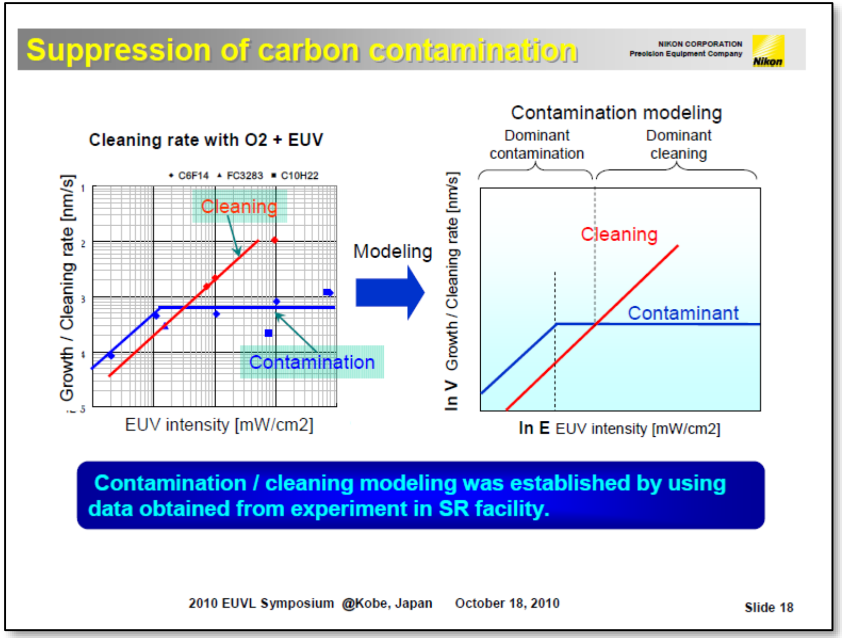
Figure 2. Transmission of 13.4 nm EUV through noble gases.

One of the enablers for EUV Lithography. One of the reasons for ASML to start with EUV!

MITIGATION



Miyaki *et al*, EUVL symposium 2010



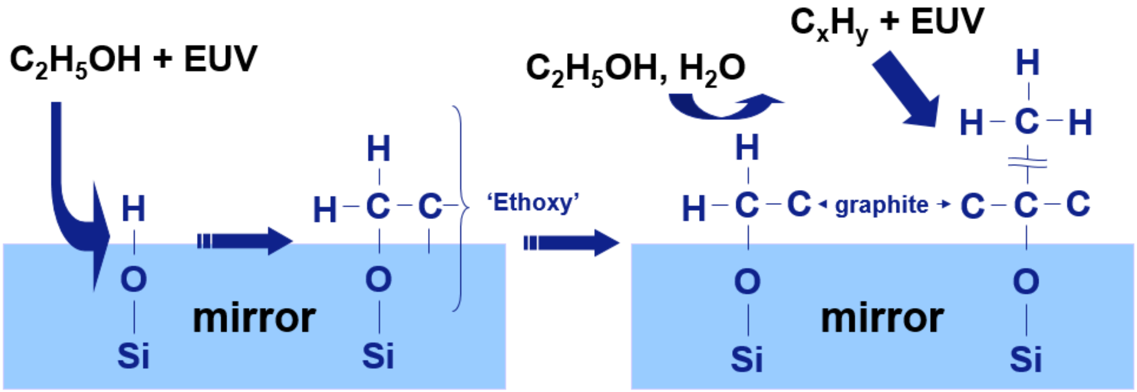
Kawai *et al*, EUVL symposium 2010

MITIGATION

- Heavy hydrocarbons disrupt process → slowly replace volatiles with non-volatiles
- Balancing very difficult

Prevention of oxidation:
admission of EtOH* (Klebanoff et al)

•EtOH + EUV creates a void-free monolayer of carbon
•surface now is hydrophobic, therefore strongly reduced H_2O-induced oxidation
•C-growth continues due to contamination hydrocarbons!



Balancing gas phase chemistry is the trick!

MNE 2001
N. Koster/16

Koster *et al*, MNE 2001

CLEANING

In-Situ Cleaning Experiments Based on Carbon Volatilization Using Oxygen or Hydrogen

•Cleaning Strategy:

Volatilization Reactions

$C + O \rightarrow CO\uparrow$
$C + 2O \rightarrow CO_2\uparrow$
$xC + yH \rightarrow C_xH_y\uparrow$

→

Generate Oxygen atoms with remote RF-discharge

Generate Hydrogen atoms with remote RF-discharge or Thermal Cracking over a hot tungsten filament.

Expose in Line-Of-Sight Conditions

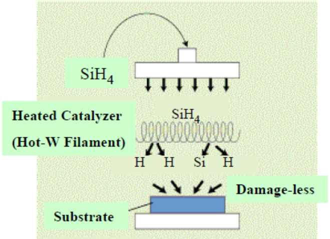
•Samples: 100 Å Carbon on Si Wafer — Determine Carbon Etch Rate

Bare Si-capped Mo/Si optics
Bare Ru-capped Mo/Si optics — Determine "Overshoot" Risks to Optics

•Post Evaluation of Samples:
At-wavelength reflectivity
Auger depth profiling

VNL Virtual National Laboratory — EUV Contamination Workshop 2003 — EUVL

Cleaning of Carbon Contamination with Catalytic or Hot-Wire CVD Apparatus



Catalytic (Hot-Wire)-CVD

Radical Formation by Heated Catlyzer (Hot-Wire Filament)

- no plasma damage
- large-area homogeneous film formation
- high radical density ($\sim 10^{14}/cm^3$)
- Resist can be removed.

This Work

Apply to atomic hydrogen cleaning of carbon contamination on Mo/Si multilayer to aim highly speedy and damage-less cleaning

Sample preparation:
- Mo/Si Multilayer sputtered on Si wafer
- Carbon deposited on Multilayer

Measurement:
- Surface carbon amount by XPS
- Carbon film thickness by optical system
- EUV reflectivity by reflectometer

2004.11.2 EUV Symposium H. Oizumi — ASET EUV Process Technology

CLEANING

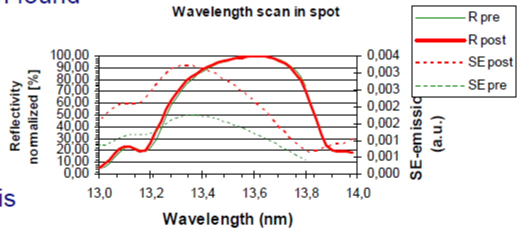
- Shielded Microwave Induced Remote Plasma
- Hydrogen as active species for metal capping layer
- Oxygen for oxide capping layer

SMIRP Cleaning Results

Over-exposure of sample EUV multilayer mirror, equivalent to 11.6 nm C-removal:

- No reflectivity loss
- No degradation of capping layer
- No cross contamination found with XPS analysis

	Pre	Post	Difference	
Date	17-10-08	23-09-2009	48,7	weeks
R (%)	100,00	99,997	**0,00**	**ΔR**
CTW96 (nm)	13,612	13,607	**-0,005**	**nm**
CTW50 (nm)	13,555	13,542	**-0,013**	**nm**
FWHM (nm)	0,581	0,584	**0,002**	**nm**
SE peak (nm)	13,36	13,34	**-0,027**	**nm**



Reflectivity is normalised!

10 New developments in cleaning of EUVL mirrors and reticles Prague, October 18 - 21, 2009

Koster *et al*, EUVL 2009

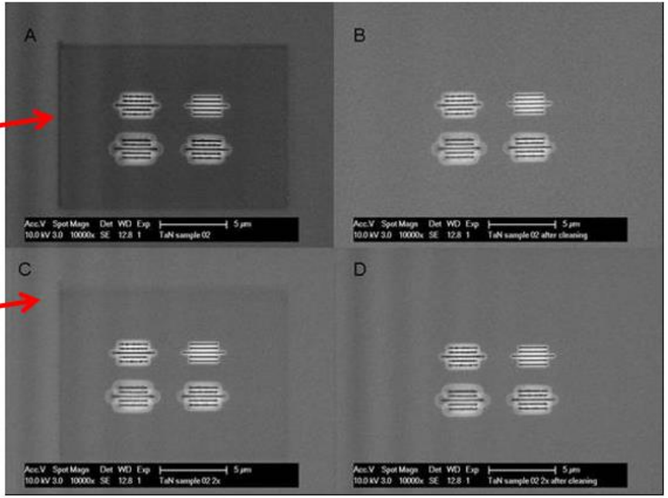
CLEANING

SPIE Advanced Lithography 2012

Plasma cleaning of TaN

7 min SEM exposure

Second 7 min SEM exposure



20 min plasma

20 min plasma

80 nm lines in 400 nm TaN, with approxiamately 2 nm C

Koster *et al*, SPIE 2012, 83220R

PAST CONCLUSION

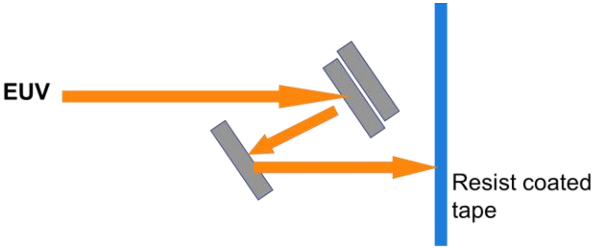
- Major showstopper for EUVL is solved
- Optics lifetime for carbon contamination under control by clean vacuum and in-situ cleaning tools
- Reticle contamination and lifetime still an issue
- Only one working point where EUV intensity, CxHy pressure, O2 pressure are balanced. Otherwise either carbon growth or oxidation will occur
- Surface coverage by light hydrocarbons is not stable. Light hydrocarbons will be replaced by heavy hydrocarbons over time

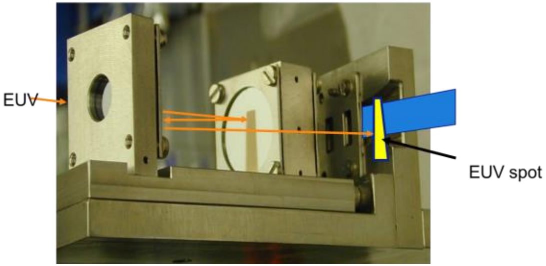
PRESENT

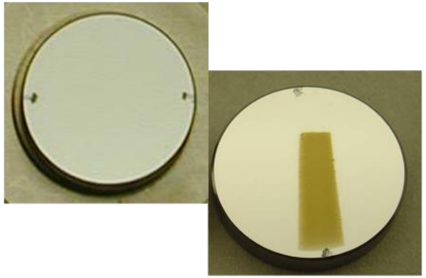
- Resist outgassing
- EBL0/1/2
- Collector lifetime
- Reticle lifetime
- Pellicle lifetime

RESIST OUTGASSING

- First proposal for resist testing by TNO/ASML/Carl Zeiss in 2006
- Procedure by ASML established in 2007







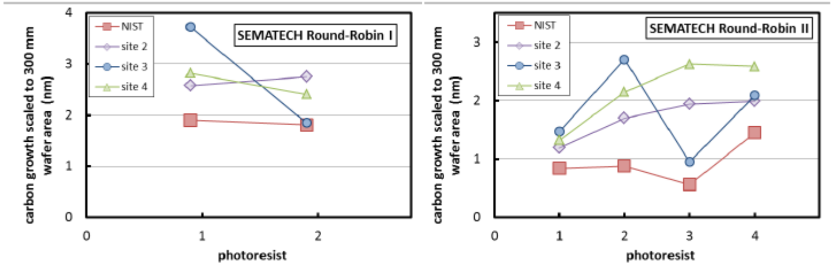
Before and after exposure → DR/R = -33%
→ Carbon spot mimics EUV beam shape

RESIST OUTGASSING

- Many sites invest in resist outgassing test set-ups according to ASML procedure
- Large differences between sites and excitation method (EUV or e-beam)
- 2015 ASML drops resist outgassing rate specifications
- New metal oxide resists evolve, contamination issues not known.
- 2017 IMEC to receive DGL membrane, enabling metal oxide resist testing

Sematech outgas testing Round Robins

Organized by Karen Petrillo and Jaewoong Sohn, Sematech



Only sites 2 and 4 showed similar trends in Round Robin II

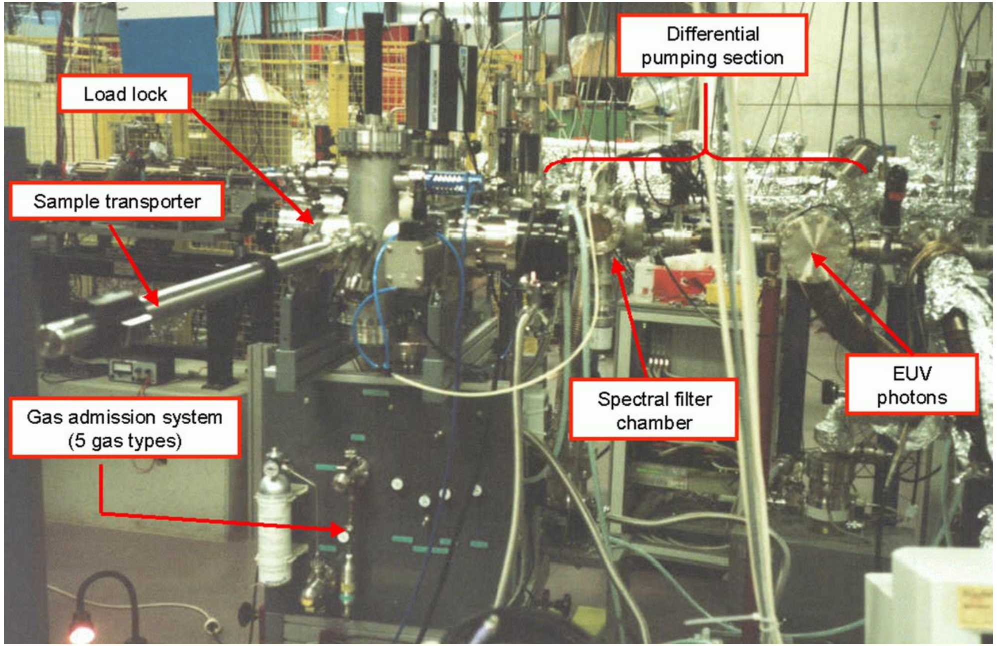
NIST values consistently lower than others in both Round Robin I & II

Physical Measurement Laboratory

Tario *et al*, EUV workshop 2014, Maui

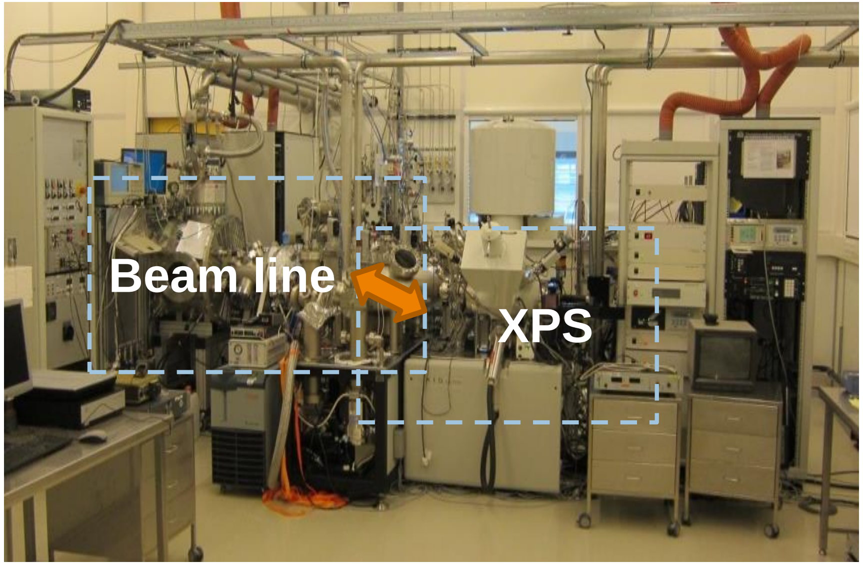
OPTICS LIFETIME @TNO

- Beamline at Bessy II
- Semi continuous EUV beam
- Established 2001
- Still operated by PTB



TNO/Carl Zeiss/PTB

OPTICS LIFETIME @TNO



TNO/Carl Zeiss

EBL established 2006
Xe source

TNO

EBL2 realized 2017
Sn source

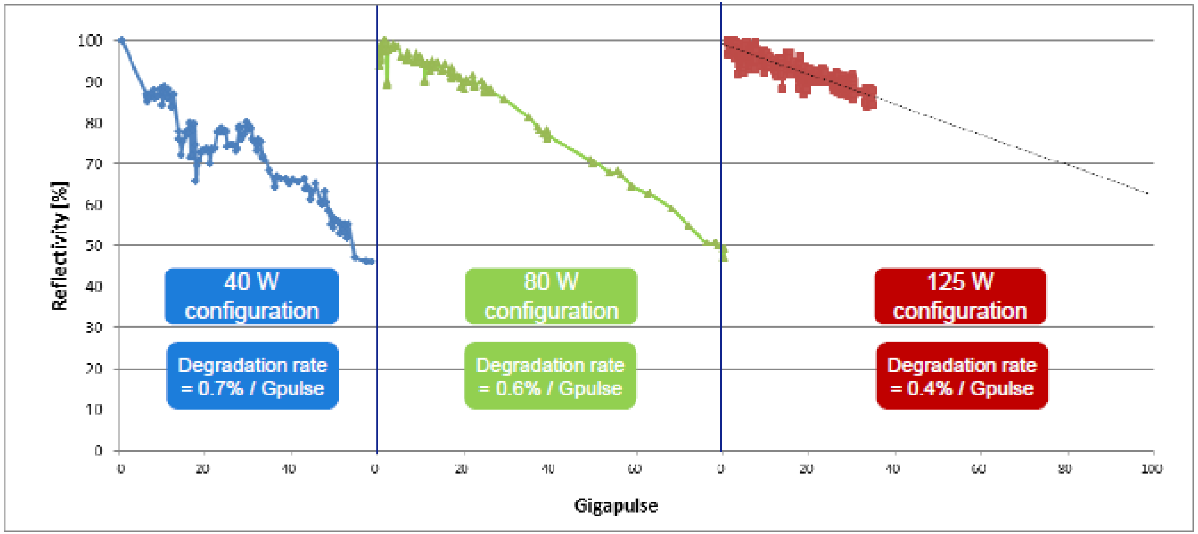
EBL2 KEY PERFORMANCE

- Clean background environment to have full control of environmental conditions
- In tool surface analysis by XPS and imaging ellipsometry
  - EUV reflectometry will be added later
- Flexible system: custom samples, gases, geometries possible
- Accepts EUV reticles and returns them in NXE compatible state

Power	>1 W in 2% BW @ 13.5 nm (“IB”) (~10 W 10-20 nm)
Power density	>1 W/mm^2 IB in focus
Spot size	1 – 30 mm diameter (power density scales)
Rep rate	1 Hz – 10 kHz (standard 3 kHz)
Sample size	Max 152x152x20 mm (reticle + pellicle possible)
Dose control	<20 % in free running experiment
Uninterrupted exposure time	>100 hours

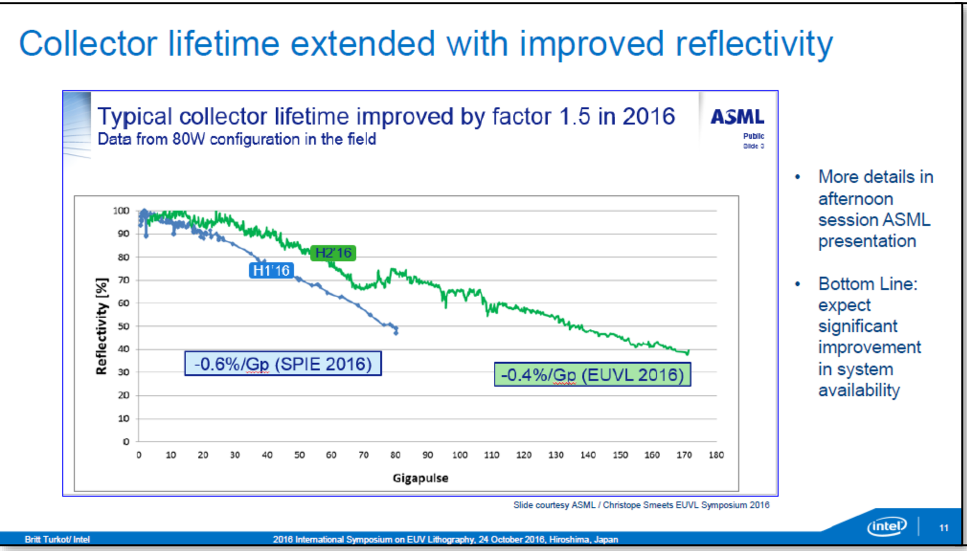
COLLECTOR LIFETIME

- Cymer increased lifetime of collector with increasing EUV powers
- Cleaning of Sn in-situ shown (2014) by ASML

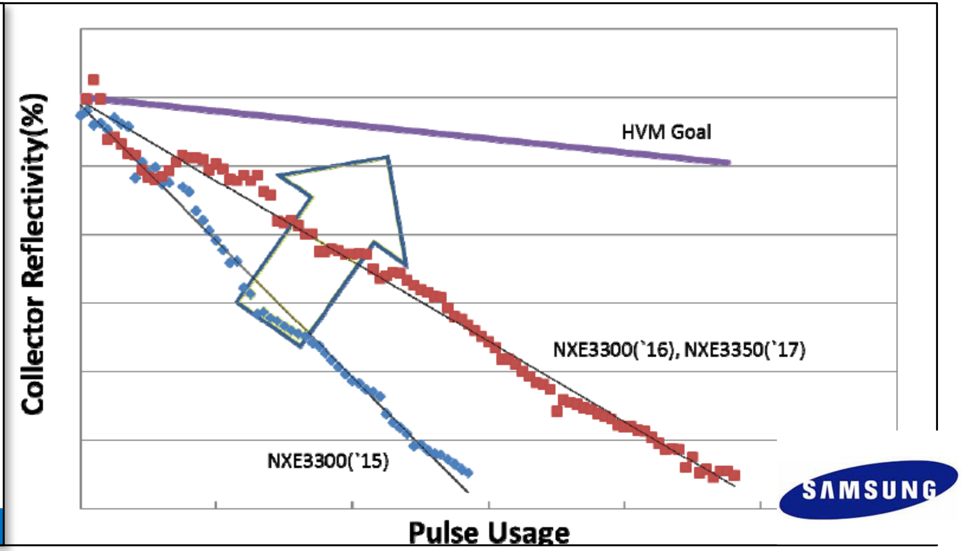


Pirati *et al*, SPIE 2016, Proc. of SPIE Vol. 9776 97760A-8

COLLECTOR LIFETIME



Turkot *et al*, EUVL symposium 2016



Kim *et al*, SPIE 2017, Proc. of SPIE Vol. 10143-06

PRESENT CONCLUSIONS

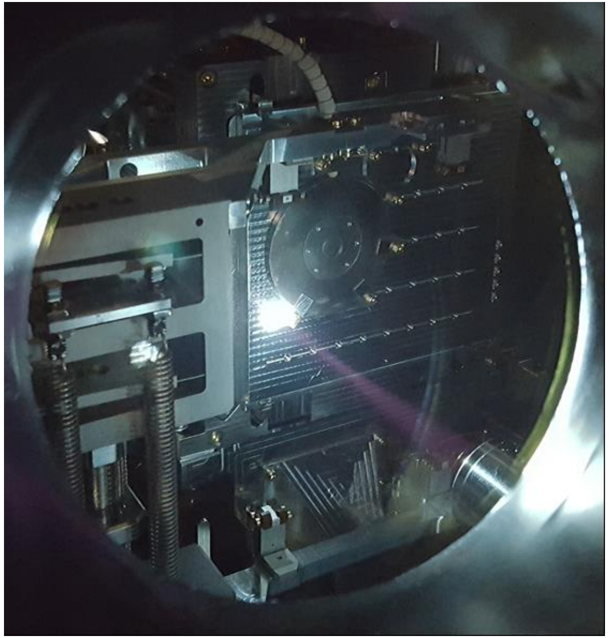
- Collector lifetime moving in the right direction
- Reticle defectivity almost up to HVM specifications but still a problem for HVM
- Pellicle is a must to ensure HVM production

FUTURE

- EUV induced plasma
- Surface chemistry
- Material/photon/ion interaction
- 1 kW EUV source

EUV INDUCED PLASMA

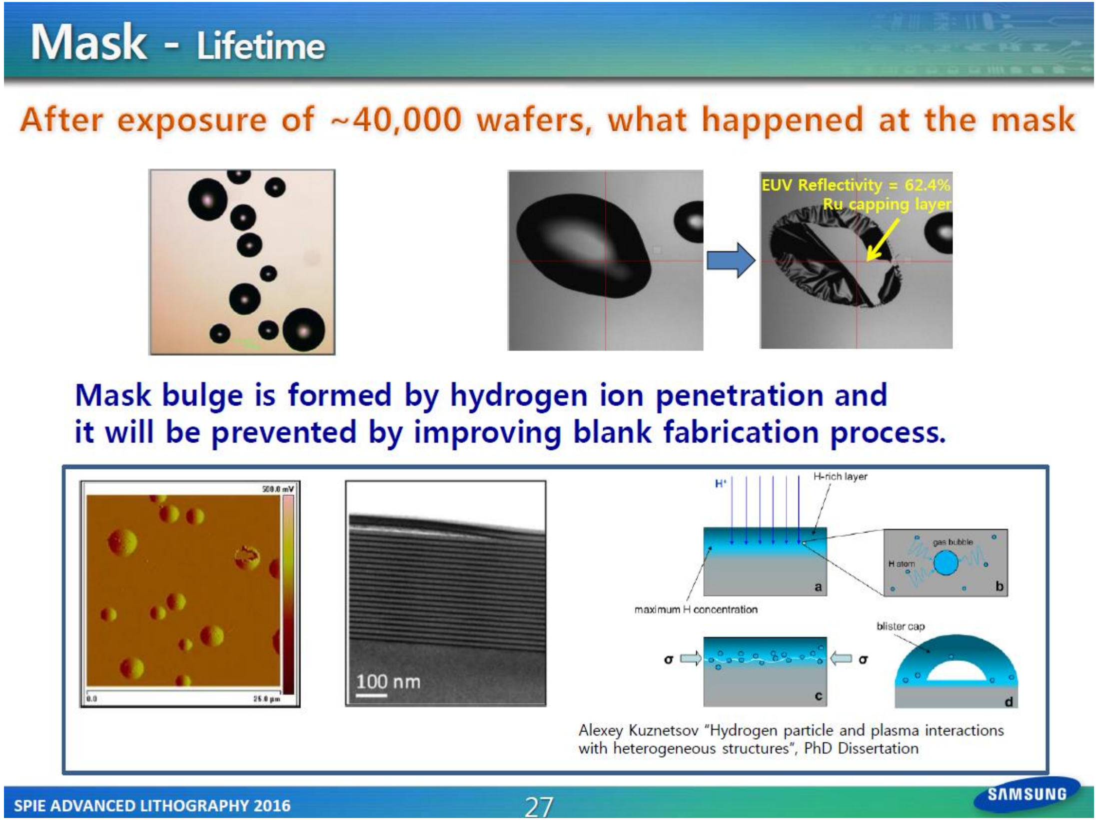
- Increasing powers and power densities will generate ions and radicals →self cleaning
- Ion energy can reach up to tens of eV (sputtering)



H2 plasma in EBL2

MASK

- Bubble formation at high powers
- Damage mechanism similar to fusion technology?
- Collector lifetime at high powers?
- Pellicle needed for defectivity



Kim *et al*, SPIE 2016

PELLICLE

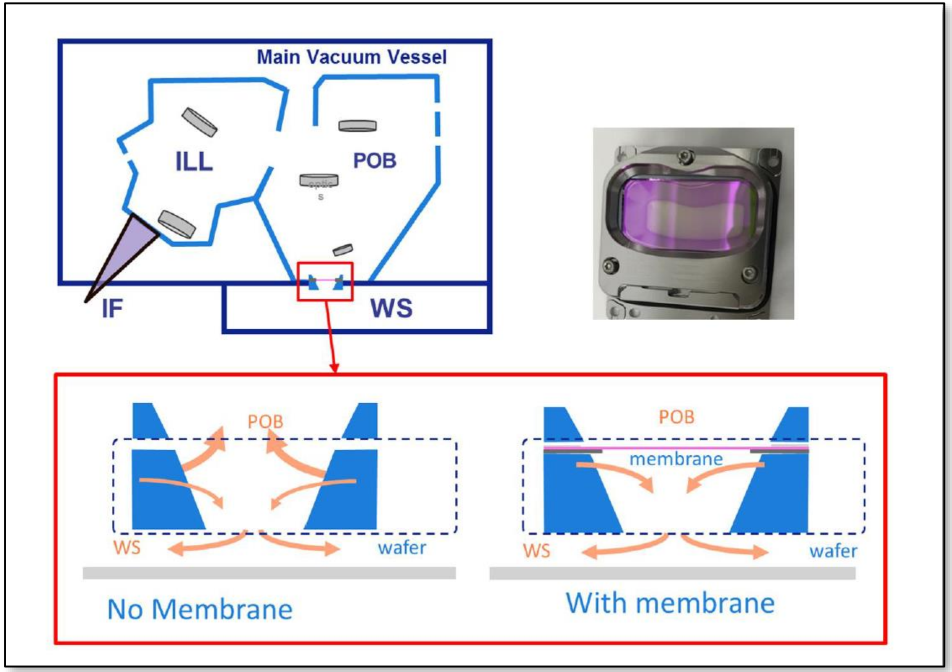
- Much work already done
- How about lifetime? Increasing EUV powers → heating, warpage, pinholes
- Printing effects

Fomenkov *et al*, EUVL workshop 2016

RESIST

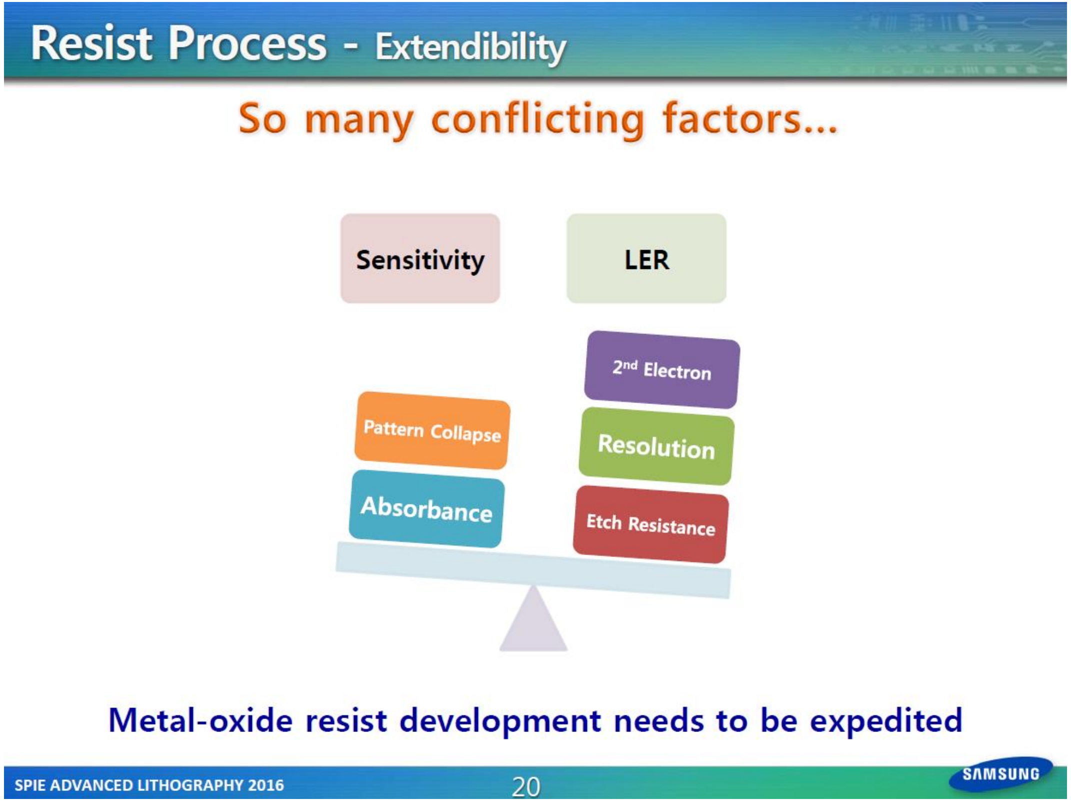
- New formulations
- Nano particles
- Metal oxides

- DGL membrane to solve outgassing issues of metallic components into optics region



Improvements in resist performance towards EUV HVM
Oktay Yildirim et al, ASML, Proc. of SPIE Vol. 10143, 101430Q

RESIST



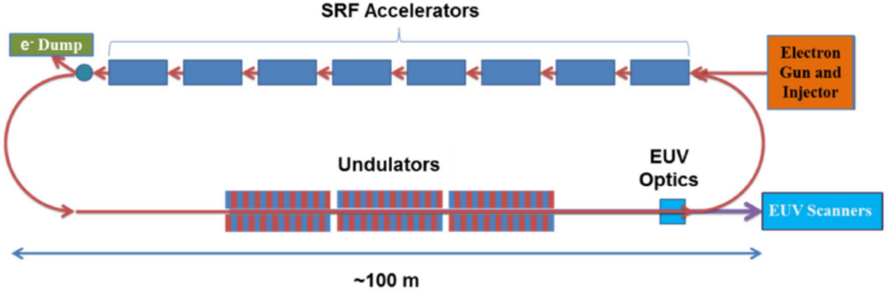
Kim *et al*, SPIE 2016

1 KW EUV SOURCE

- Is a FEL an option?
  - Beam delivery and beam splitter
  - Reliability
  - Uptime
- How far can we stretch LPP sources?
  - Droplet rep rate
  - Laser rep rate
  - Conversion efficiency
  - Sn contamination

More Powerful & Efficient EUV Source

- Key components of a free-electron laser (FEL) EUV source



Item	Target	Motivation/Implication
Power	>20 kW	Ten 1kW scanners (50% transport loss)
Availability	>99%	Some redundant system hardware required
CoO	~$250M CapEx, ~$20M OpEx	2x better than CoO for 10 LPP sources
General Configuration	Energy Recovery LINAC @ ~2K SASE Output	Maximize efficiency & minimize cost
Timing	TBD	To intercept high-NA EUV scanner insertion

Ref: E. Hosler et al., "Considerations for a free-electron-laser based extreme-ultraviolet lithography program," Proc. SPIE 9422, 94220D (2015).

2016 EUV Lithography Symposium 22

Wood *et al*, EUVL symposium 2016

CONCLUSION

- We are moving into HVM, with associated problems:
  - Reliability
  - Increasing EUV powers
- Contamination control went from simple carbon contamination to complex photon/material interaction
  - New cap layers needed?
  - Material research

- We are almost at the end of the tunnel and the light is getting brighter

ACKNOWLEDGEMENTS

Everybody working in the EUV community, without you this could not have happened

ASML, ZEISS, SAMSUNG, tsmc, CYMER An ASML company, Canon, GLOBAL FOUNDRIES, NIST, intel, SEMATECH SUNY POLYTECHNIC INSTITUTE, COLLEGES OF NANOSCALE SCIENCE + ENGINEERING SUNY POLYTECHNIC INSTITUTE, Selete, FOM, PTB, ASET, BERKELEY LAB Lawrence Berkeley National Laboratory, SEMATECH, CXRO THE CENTER FOR X-RAY OPTICS, EUVA, Nikon

THANK YOU FOR YOUR ATTENTION

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